12-2019

# Nematode Populations as Affected by Residue and Water Management in a Long-term Wheat-soybean Double Crop in Eastern Arkansas

Lucia Emperatriz Escalante Ortiz
*University of Arkansas, Fayetteville*

Nematode Populations as Affected by Residue and Water Management in a Long-term Wheat-soybean Double Crop in Eastern Arkansas

A thesis submitted in partial fulfillment
of the requirement for the degree of
Master of Science in Crop, Soil, and Environmental Sciences

by

Lucia Emperatriz Escalante Ortiz
National University of Cajamarca
Bachelor in Agronomy, 2011

December 2019
University of Arkansas

This thesis is approved for recommendation of the Graduate Council.

Kristofor R. Brye, Ph.D
Thesis director

Lisa S. Wood, Ph.D
Committee Member

Leandro Mozzoni, Ph.D
Committee Member

Travis Faske, Ph.D
Committee Member

## Abstract

Soybeans (*Glycine max)* are one of the major row crops in the United States, particularly in Arkansas. Soybean cyst nematode (SCN, *Heterodera glycines*) and southern root-knot nematode (RKN, *Meloidogyne incognita*) are two of the most damaging pests that cause major economic losses in soybeans. Little is known concerning the effects of common and alternative agronomic practices on nematodes in fields with nematode population densities below threshold levels. Therefore, the objective of this study was to evaluate the effects of the combination of tillage (conventional tillage and no-tillage), irrigation (irrigated and non-irrigated), wheat (*Triticum aestivum*) residue burning (burned and no burned), and wheat residue level (high and low) on the natural nematode population density and change over the growing season and between years in a long-term, wheat-soybean rotation on a silt-loam soil in Arkansas. Nematodes were measured in the top 10 cm in July, August, and October 2017 and 2018. The SCN egg population density in the soil was numerically largest [$P$ = 0.01; 2.9 nematodes (100 $cm^3)^{-1}$] in the conventional tillage (CT)-no-burn combination under irrigated conditions and lowest [0.1 nematodes (100 $cm^3)^{-1}$] in the CT-no-burn combination under dryland production. The SCN J2 population densities [1.1 nematodes (100 $cm^3)^{-1}$] was 3.4 times greater ($P$ < 0.01) under the CT-burn than under the CT-no-burn and no-tillage (NT)-burn treatment combinations, which did not differ and averaged 0.49 nematodes (100 $cm^3)^{-1}$. Spiral nematode (*Helicotylenchus* spp.) population densities was 52.6 times greater ($P$ < 0.01) under irrigated-CT [31.84 nematodes (100 $cm^3)^{-1}$] than under the irrigated-NT, dryland-CT, and dryland-NT treatment combinations in 2017, all of which had less than 0.6 nematodes (100 $cm^3)^{-1}$. Lesion nematode (*Pratylenchus* spp.) population density was 5.6 times greater ($P$ = 0.02) under the dryland-burn than under the dryland-no-burn treatment combination, but was unaffected by burning under irrigated

conditions. The RKN had small populations in the soil and could not be formally statistically analyzed. Traditional and alternative wheat-soybean management practices can influence nematode populations and should be carefully considered to maximize soybean production and profitability.

## Acknowledgements

I would like to thank Dr. Brye for taking the risk of having me as his student. I could not be more grateful for all the support, guidance, and patience with me during my journey in graduate school. Dr. Brye has that passion for teaching and advising students that inspires and motivates me to love science and academia.

I would like to thank to Drs. Lisa Wood, Leandro Mozzoni and Travis Faske for serving on my committee and for providing valuable advice on my research. I also would like to thank Dr. Edward E. Gbur and Kevin Thompson for assisting me with statistics throughout my research.

I would like to thank my lab mates, Becky Anderson, Ryder Anderson, Niyi Omidire, and Shelby Lebeau who provided me field or laboratory assistance.

I would like to thank my family for their unconditional support throughout my time at the University of Arkansas. Also, I would like to thank my fiancé for his unconditional support.

I would like to thank Dr. Joe Gergerich for been my English tutor and helping me to improve my English skills.

I would like to thank the Association the Andes of Cajamarca and Fulbright Peru for making possible to achieve one of my dreams. Finally, I want to thank the Soybean Promotion Board for partially funding this research.

## Dedication

This thesis is dedicated to my family, the Fulbright Program, the Association the Andes of Cajamarca, friends, and all the people who believe on me.

## Table of Contents

## List of Tables

**List of Figures**

# Introduction

Plant-parasitic nematodes are one of the most damaging pest of soybean production in the United States, causing an average of 31% of yield losses from 2010 to 2014 (Allen et al., 2017). Wrather and Koennig (2006) reported that *Heterodera glycines* (Soybean Cyst Nematode; SCN) is the main yield-limiting pest of soybean production in the U.S., which in 2005 caused more than $ 1 billion in yield losses. By growing SCN resistant cultivars, using crop rotation, reducing tillage, and using nematicides yield losses can be reduced. However, there are limited soybean cultivars with resistance to SCN (Niblack and Chen, 2004). The soybean cyst nematode *Meloidogyne incognita* (root-knot nematode, RKN), and *Rotylenchus reniformis* (reniform nematodes) are the most damaging for soybean production in Arkansas (Arkansas Soybean Promotion Board, 2019). Crop rotation with non-host cultivars are considered the most effective nematode control (Niblack and Chen, 2004). Moreover, tillage management practices such as minimum tillage might minimize the nematodes infestation in the soil. For years, nematicides have been used to control nematode infestation in crop production systems; however, many nematicides have been banned because nematicides can harm the environment and human health (Ferris et al., 2012). Several studies conducted in the U.S. have concentrated on the effects of tillage, crop rotation, and water management on nematodes population in soybeans (Johnson et al., 1994; Noel and Wax, 2003; Brye et al., 2018). However, there is a little information regarding the effects of the combination of tillage, irrigation, burning, and residue level in a long-term rotation of wheat-soybean on a silt loam soil in the U. S., specifically in Arkansas. Also, a little previous research has shown whether or not residue burning, or non-burning affects nematode populations in the USA. The aim of the research is to evaluate the combined long-term effects of tillage practices (conventional tillage and no tillage), water management (irrigation and non-irrigation), residue burning (burned and non-burned), and wheat residue level (high and low) on parasitic nematode population density and reproduction in the top 10 cm after 15 years in a wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

## Literature Cited

Allen, T. W., Bradley, C. A., Sisson, A. J., Byamukama, E., Chilvers, M. I., Coker, C. M., Collins, A. A., Damicone J. P., Dorrance, A. E., Dufault, N. S., Esker, P. D., Faske. T. R., Giesler, L. J., Grybauskas, A. P., Hershman, D. E., Hollier, C. A., Isakeit, T., Jardine, D. J., Kelly, H. M., Kemerait, R. C., Kleczewski, N. M., Koenning, S. R., Kurle, J. E., Malvick, D. K., Markell, S. G., Mehl, H. L., Mueller, D. S., Mueller, D. J., Mulrooney, R. P., Nelson, B. D., Newman, M. A., Osborne, L., Overstreet, C., Padgett, G. B., Phipps, P. M., Price, P. P., Sikora, E. J., Smith, D. L., Spurlock, T. N., Tande, C. A., Tenuta, A. U., Wise, K. A., and Wrater, J. A. 2017. Soybean yield loss estimates due to diseases in the United States and Ontario, Canada, from 2010 to 2014. Plant Health Progress 18:19-27.

Arkansas Soybean Promotion Board (ASPB). 2019. Controlling harmful effects of nematodes [Online]. https://www.themiraclebean.com/controlling-the-harmful-effects-of-nematodes-2/ (verified 25 Nov., 2019).

Brye, K. R., Quarta, M., Morrison, C., and Rothrock, C. 2018. Long-term effects of residue and water management practices on plant parasitic nematode abundance and soybean root infection. Applied Soil Ecology 124:275-283.

Ferris, H., Griffiths, B. S., Porazinsca, D. L., Powers, T. O., Wang, K., and Tenuta, M. 2012. Reflections on plant and soil nematodes ecology: past, present, and future. Journal of Nematology 44:115-126.

Johnson, A. B., Scott, H. D., and Riggs, R. D. 1994. Response of soybean in cyst nematode-infested soils at three soil-water regimes. Journal of Nematology 26:329-335.

Niblack, T. L., and Chen, S. Y. 2004. Cropping systems Pp. 181-206 *in* D. P. Schmitt, R. D. Riggs, and J. A. Wrather, eds. Biology and management of soybean cyst nematode. Marceline, MO, USA: Schmitt and Associates of Marceline.

Noel, G. R., and Wax, L. M. 2003. Population dynamics of *Heterodera glycines* in conservation tillage and no-tillage soybean/corn cropping systems. Journal of Nematology 35:104-109.

Wrather, J. A., and Koenning, S. R. 2006. Estimate of disease effects on soybean yields in the United States 2003 to 2005. Journal of Nematology 38:173-180.

# Chapter 1

# Literature Review

## Nematodes

### General Definition and Population Densities

Nematodes are unsegmented, multicellular roundworms (Hartman et al., 2015) that have limited mobility in the soil (Fujimoto, et al., 2010). Nematodes have soft bodies (Lambert and Bekal, 2002), feed on a wide range of food sources, such as plants, fungal hyphae, algae, bacteria, protozoa, and other nematodes (Khan, 2008), and can live in nearly all ecological niches from the desert to the snowy mountains (Hartman et al., 2015 and Khan, 2008).

Nematodes can live in any climate that supports plant life (Bridge and Starr, 2007). Consequently, soil and plant nematodes are the most abundant organisms living in the soil (Hartman et al., 2015). More than 20,000 nematodes can be found in 250 $cm^3$ soil sample, which is equivalent to 7.5 billion nematodes in the top 15 to 20 cm of 1 ha of any soil type (Hartman et al., 2015). However, only a few nematode species are capable of parasitizing plants (Khan, 2008).

### Morphology and Growth Habits

The majority of plant-parasitic nematodes are microscopic; however, a few species, such as the adult female and cyst phase of soybean [*Glycine max*) Merr.] cyst nematode (SCN; *Heterodera glycines*) can be seen without the aid of a magnification (Hartman et al., 2015; Bridge and Starr, 2007). The shape of juvenile and adult nematodes is flexible and cylindrical. (Hartman et al., 2015). Females of cyst nematodes (*Heterodera* spp. and *Globodera* spp.), the root-knot nematode (*Meloidogyne* spp.), false root-knot nematode (*Nacobus* spp.), and reniform nematode (*Rotylenchus* spp.) have evolved to take on a swollen, sac-like shape (Hartman et al., 2015). Nematode reproduction is sexual, and asexual (parthenogenic) (Bridge and Starr, 2007).

Some female nematode genera have the ability to lay more than 1,000 eggs, while other nematode genera lay less than 50 eggs (Bridge and Starr, 2007). Reproduction ability depends of the species and is influenced by the nematode's surrounding environment and host (Hartman et al., 2015).

The life cycle of most plant-parasitic nematodes consists of an egg, four juvenile (J) stages, and finally, the adult and reproductive stage (Hartman et al., 2015; Bridge and Starr, 2007). In the majority of plant-parasitic nematode the J2 hatch from the egg (Hartman et al., 2015). The duration of the nematode life cycle depends on the genera, but in general, ranges from a few days to almost one year under favorable environmental conditions and plant hosts (Bridge and Starr, 2007).

Nematodes can survive in the soil through different mechanisms of dormancy (diapause and quiescence) (Karssen and Moens, 2006). The RKN J2 can survive in the soil for long periods of time consuming their food reserves stored in their intestines (Karssen and Moens, 2006). The eggs and juveniles of the genera *globodera* and *heterodera* survival in the soil is longer than the *Meloidogyne* genera due to eggs in cysts remain viable in the soil for several years (Karssen and Moens, 2006).

**Nematode Types**

Nematodes can be generally categorized as plant-parasitic or non-parasitic. Plant-parasitic nematodes have to live on or very near living plant tissues to complete their life cycle (Hartman et al., 2015). The parasitic behavior of nematodes in soybeans and other upland crop plants varies among the different nematode species (Hartman et al., 2015). Among the plant-parasitic nematodes, some are ectoparasitic, which is a parasite that live on the surface of their host, while others are endoparasites that lives inside the host (Bridge and Starr, 2007).

Migratory ectoparasites live on the surface of plant tissues and feed by inserting their stylet into plant cells. Migratory ectoparasites include many genera and species, but only a few cause damages to crops (Bridge and Starr, 2007). Some species of nematodes that cause damage to cultivated crops are: sting nematode (*Belonolaimus longicaudatus*), sheath nematode (*Hemicycliophora arenaria*), dagger nematode (*Xiphinema* spp.), needle nematodes (*Longidorus* spp., *Paralongidorus* spp.), and stubby root-knot nematodes (*Trichodorus* spp, *Paratrichodorus* spp.) (Bridge and Starr, 2007). The stunt nematode (*Tylenchorhynchus* and *Merlinius* spp.) and ring nematode (*Criconemoides* spp.); these nematodes cause yield losses in some crops (Bridge and Starr, 2007). Some species of spiral (*Helicotylenchus* spp.) and reniform nematodes also feed as ectoparasites. Migratory ectoparasites can feed on leaves, flowers, stems, and roots (Bridge and Starr, 2007). Nematodes move passively in soil water, soil, contaminated plant tissues, infected insect vectors, and on tools, vehicles, and machinery contaminated with nematode-infected soil (Hartman et al., 2015). However, without other influences, nematodes movement on their own in the soil is generally limited to within 1 m per year (Lambert and Bekal, 2002).

Migratory endoparasites usually migrate between the soil and roots (Bridge and Starr, 2007). Migratory endoparasites can completely penetrate into plant tissues and can continue moving and feeding as they migrate in the plant tissues (Bridge and Starr, 2007). The genera *Pratylenchus, Radopholus, Hirschmanniela, Hoplolaimus, Scutellonema*, *Aphasmatylenchus*, *Helicotylenchus*, *Ditylenchus*, and *Reniformis* nematode are well-studied endoparasitic species that harm crops (Bridge and Starr, 2007). Some ectoparasitic (*Aphelenchoides*, *Ditylenchus angustus* and *D. dispaci* and others), in all stages, can infect stems, leaves, flowers, roots, corms, bulbs, tubers, and seeds [e.g., peanut (*Arachis hypogaea*)] (Bridge and Starr, 2007).

Sedentary endoparasitic nematodes are nematodes whose immature female or juveniles completely enter plant tissues, form a stable feeding spot, become immobile, and form galls or cysts (Bridge and Starr, 2007). The main species of sedentary endoparasites are *Achlysiella, Globodera, Heterodera, Meloidogyne, Nacobbus,* and *Pundoctera* spp. (Bridge and Starr, 2007).

Semi-endoparasitic nematodes are those whose immature females or juveniles partially enter root tissues and leave half to two-thirds of their body outside the root tissue (Bridge and Starr, 2007). *Rotylenchus, Sphaeronema, Trophotylenchulus,* and *Tylenchulus* spp are migratory endoparasites that can behave as semi-endoparasites on plant roots (Bridge and Starr, 2007).

## Factors that Affect Nematodes

### *Environmental Factors*

Plant-parasitic nematodes are mostly aquatic and need free moisture to develop (Bridge and Starr, 2007). Plant-parasitic nematodes live in moisture-containing spaces around soil particles and in the moisture surrounding plant tissues (Bridge and Starr, 2007). Soybean cyst nematode has better development at about -0.03 MPa to -0.04 MPa than at above -0.05 MPa in the top 0.15 m (Heatherly et al., 1982). Soil moisture levels of 40 to 60% favors *Meloidogyne* species activity (Karssen and Moens, 2006). Soil moisture enhances the potentially harmful effects of plant-parasitic nematodes on crops (Koenning and Barker, 1995) because nematode mobility increases as water flows in the soil pore space, which facilitates nematodes to reach plant roots (Fujimoto et al., 2010). Also, soil moisture increases the nematode’s ability to locate, penetrate, hatch, and mate (Koenning and Barker, 1995). Nematodes migrate along soil water gradients. In dry soils, nematode migrate toward less negative potentials (more moisture), while in waterlogged soils nematode migrate toward more negative potentials. Nematode movement in waterlogged soils is restricted due to low $O_2$ levels.

Temperature is a crucial factor for nematode development (Karssen and Moens, 2006). Temperature influences the nematode distribution, survival, reproduction, and growth (Karssen and Moens, 2006). The optimal soil temperature for plant-parasitic nematode development ranges from 15 to 32$^{o}$C (Moore, 1984). The SCN has a life cycle of around 24 days when the soil temperature is 23$^{o}$C. However, SCN life cycle can take 40 days with a soil temperature of 18$^{o}$C. Usually SCN development does not occur below 10$^{o}$C or above 34$^{o}$C (Moore, 1984). The lower threshold soil temperature for normal SCN development is 14$^{o}$C, and the upper is 38$^{o}$C (Ross, 1964). Between 35 and 38$^{o}$C soil temperatures, most adult nematodes are male (Tyler et al., 1987).

*Soil Properties*

Soil texture and other soil properties, such as pore size and soil water-holding capacity are important aspects that influence nematode impact on crops (Heatherly and Young, 1991). Soil properties can positively or negatively influence egg development, hatch rate, survival, migration, and infectivity of several nematode species (Heatherly and Young, 1991). In coarse-textured soils with relatively large pore spaces (i.e., more than 60% sand content), nematodes commonly cause crop problems (Heatherly and Young, 1991). Nematodes can also be a problem in soils rich in organic matter with a moderate degree of soil particle aggregation between silt and clay so that the pore space increases (Bridge and Starr, 2007). Greater numbers of SCN females and eggs were reported in a sandy-loam than in silt-loam textured soils eight weeks after the introduction of the same number of eggs and juveniles (Schmitt et al., 1987).

Soybean cyst nematode reproduction was reduced in fine- compared to coarse-textured soils because nematode reproduction is low in soils with limited space for nematodes movement (Koenning and Barker, 1995). Soil compaction and nematode infections often occur together and reduce soybean crop yields because tillage causes soil compaction and increases nematode infestation in the soil due to nematodes spread by machinery implements (Minton, 1986; Parker et al., 1975). In general, nematode damage has been reported in almost all soil textures (Bridge and Starr, 2007).

*Tillage Management Practices*

Tillage practices can have an effect on nematodes. Reduced tillage might reduce nematode reproduction and distribution because nematodes can be transported on machinery implements (Minton, 1986).  It has been observed that soil disturbance caused an increase in the SCN egg population due to that nematode inoculum is horizontally distributed in the field (Bao et al., 2011). However, no tillage may increase the vertical nematode concentration in the soil profile. In compacted soils, minimum tillage might limit soil volume available to roots and root penetration, which resultant moisture stress can increase nematode crop injury (Minton, 1986). Crop residues left on the soil surface have the potential to increase the nematode populations and soil microorganisms due to the changes in soil moisture and temperature (Minton, 1986). Under clean fallow practices, nematode population is usually reduced. (Minton, 1986). Low soil temperatures can alter nematode growth in no tillage (NT) systems compared to conventional tillage (CT) (i.e., residue free) systems because crop residues left in the soil in the NT systems decrease soil temperature, thus decreasing nematode reproduction (Tyler et al., 1987).

**Plants Affected by Nematodes**

All crops are prone to be infected by at least one nematode species (Bridge and Starr, 2007). In the U.S. corn (*Zea mays*) production, the most frequently reported genera of nematode are lance nematode (*Hoplolaimus* spp.), root-knot, and lesion nematode (Koenning et al., 1999). Also, Simon et al (2018) reported that dagger, ring, lance, stunt, pin, stubby root, and spiral nematode are associated with corn in Ohio. Soybean is susceptible to SCN, root-knot, lesion, and reniform nematodes (Koenning et al., 1999). Wheat (*Triticum aestivum*) parasitic nematodes include the cereal cyst nematode (*Heterodera avenae*), root-knot nematode, ring nematode (*Mesocriconema* spp.), and lesion nematode (Koenning et al., 1999). In grain sorghum (*Sorghum bicolor*) production, the most frequently reported nematodes are the sting, root-knot nematode, and lesion nematode (Koenning et al., 1999). In sugarcane (*Saccharum officinarum*) production, the sting nematode and root-knot nematode are considered to be the most damaging (Koenning et al., 1999). In cotton (*Gossypium hirsutum)* production, the root-knot and the reniform nematode are commonly related to cotton yield losses (Koenning et al., 1999). Peanut yield losses were attributed to the peanut root-knot nematode (*Meloidogyne arenaria*) and other species of Meloidogyne, (also sting is an important issue in GA). Root-knot nematode (Koenning et al., 1999). In addition, tobacco *(Nicotiana tabacum*) is susceptible to the majority of the genera of the root-knot nematode. The nematode genera that cause losses in alfalfa (*Medicago sativa*) are the stem nematode (*Dilylenchus dipsaci*), root-knot, and lesion nematode (Koenning et al., 1999). Nematode pests in rice (*Oryza sativa*) include *Aphelenchoides*, *Ditylenchus*, rice cyst nematode (*Heterodera Oryzae), Hirschmanniella,* root-knot, and lesion nematode (Koenning et al., 1999). The most damaging nematodes that have been documented are the cyst nematodes on potatoes (*Solanum tuberosum*) in Europe (Bridge and Starr, 2007). The degree of crop damage, mainly in annual crops, is related to the nematode population density (Bridge and Starr, 2007). Nematodes can affect all plant tissues, but they are mainly root parasites (Bridge and Starr, 2007).

**Soybean History and Diversity**

Though nematodes can affect many plants, including upland and lowland crops, nematodes are particularly influential in soybean growth. Soybean is a legume native to eastern Asia (Piper and Morse, 1923) and northern China (Hartman et al., 2015). Soybean domestication was likely to have occurred during the Shang Dynasty [i.e., 1500 to 1100 before common era (BCE) or earlier]. However, soybean appeared as a domesticated plant during the Zhou Dynasty (i.e., 1046 to 256 BC) (Hartman et al., 2015).

In the world, there are more than 100,000 accessions of *Glycine max* and no more than 10,000 accessions of *Glycine soja* (Hartman et al., 2015). *G. max* and *G. soja* have genotypic and phenotypic differences (Joshi et al., 2013). *Glycine max* has 46,430 protein-coding genes (Schmutz and Cannon, 2010). There are 425 protein-coding genes that are unique in *G. max*, but are not available in *G. soja*. Twelve genes relate to seed growth, three relate to oil, and six relate to protein concentration that are exclusive to *G. max* (Joshi et al., 2013). An unknown number of accessions of *G. ma*x and *G. soja* are distributed in Japan, Russia, South Korea, Germany, India, Indonesia, Australia, Brazil, China, and the United States (Hartman et al., 2015). The United States Department of Agriculture's (USDA) soybean collection at the University of Illinois in Champaign-Urbana is one of the largest germplasm collections in the world (Hartman et al., 2015). The large soybean germplasm diversity helps scientists to investigate for genetic resistance to pests, pathogens, and weather stresses (Hartman et al., 2015).

## Soybean Growth Stages and Maturity

Soybean plants have vegetative (V) and reproductive (R) growth stages. The vegetative stages are emergence (VE), cotyledon (VC), first, second, and third nodes (V1, V2, and V3, respectively) and the $N^{th}$ number of nodes (VN). The reproductive stages are when blooming begins (R1), complete flowering (R2), beginning of pod development (R3), complete pod development (R4), beginning of seed development (R5), complete seed development (R6), beginning of maturity (R7), and complete seed maturity (R8; Fehr et al., 1971).

In North America, a maturity group (MG) system is used to indicate the area of adaptation for a cultivar. The MG ranges from 000 to X. Cultivars that mature ultra-early are designated with MG 000 and are located in Canada, which has a short growing season, while cultivars designated with MG X are adapted to tropical and subtropical regions, which have longer growing seasons (Hartman, 2015).

## Soybean Production

### *Optimum Soybean Growing Conditions*

The environment plays an important role in soybean production. The optimum soil pH for soybean is between 5.8 and 7.0 and 25 to 30$^{o}$C is the ideal air temperature for soybean growth (Hartman et al., 2015). Adequate soil preparation, depth of planting, and weed control can improve plant growth. Cultivar election, planting date, row spacing, and adequate seed distribution can alter soybean productivity (Hartman et al., 2015). Microbial associations with fungi might benefit soybean growth and drought tolerance and optimize the uptake of phosphorus (P) and other nutrients (Hartman et al., 2015). Soybean seeds should be inoculated with the N-fixing bacteria *Rhizobium japonicum* if soybeans had not been planted in a field for more than four years or if the field has been underwater (McWilliams et al., 1999). Soybean seeds should be planted 2.5 to 3.8 cm deep , but not more than 5 cm deep because deep planting can hinder soybean germination (McWilliams et al., 1999). Soybean seeds require a minimum soil temperature of 12$^{o}$C for germination. Soybean seeds also need 50% moisture seed content (dry weight) to germinate. Adequate soil moisture is crucial for homogeneous germination (Hartman et al., 2015).

Soybean plants have vegetative growth for some weeks prior to flowering, where flowering lasts approximately 2 to 4 weeks, during which time soybean plants can withstand short periods of soil moisture stress by delaying plant growth. Water supply of 0.9 cm per day should be applied to keep optimum moisture in the soil, which is crucial during reproductive stage (full blossom and pod-filling stage) (Hartman et al., 2015). In tropical regions, soybean maturity is achieved in about five months, while maturity can be achieved in as little as three months in temperate regions (Hartman et al., 2015).

**Global Production**

Soybean is an important crop around the world (Hartman el al., 2010). In 2013, soybeans were grown in 70 countries, where the leading producers were: United States (31% of total global production), Brazil (31%), Argentina (19%), China (5%), India (4%), Paraguay (3%), and Canada (2%) (Hartman et al., 2015). In 2016, soybean production in the word was led by the United States with 117.2 million megagrams (MMg) of soybeans harvested followed by Brazil (96.3 million MMg), Argentina (58.8 million MMg), India (14.0 million MMg), China (12.0 million MMg), Paraguay (9.2 million MMg), Canada (5.8 million MMg), Ukraine (4.3 million MMg), Bolivia (3.2 million MMg), and the Russian federation (3.1 million MMg) (FAO, 2019).

During the 2016-2017 soybean growing season, the average production in the world was 2.93 Mg ha$^{-1}$. In the same year, Serbia had the largest average soybean production with 3.51 Mg ha$^{-1}$ followed by the United States with 3.49 Mg ha$^{-1}$, Brazil with 3.38 Mg ha$^{-1}$, Turkey with 3.33 Mg ha$^{-1}$, Argentina with 3.17 Mg ha$^{-1}$, Paraguay with 3.05 Mg ha$^{-1}$, the European Union with 3.00 Mg ha$^{-1}$, Canada with 2.96 Mg ha$^{-1}$, Uruguay with 2.95 Mg ha$^{-1}$, Ukraine with 2.31 Mg ha$^{-1}$, South Africa with 2.29 Mg ha$^{-1}$, Zambia with 1.94 Mg/ha, Bolivia with 1.86 Mg ha$^{-1}$, Mexico with 1.85, China with 1.79 Mg ha$^{-1}$, North Korea with 1.61 Mg ha$^{-1}$, Japan with 1.59 Mg ha$^{-1}$, South Korea with 1.53 Mg ha$^{-1}$, and India with 0.98 Mg ha$^{-1}$ (FAO, 2019).

## Soybean Production in North America

In North America, soybean was introduced by Samuel Bowen 250 years ago and, by the 1940s, soybean was widely grown (Hartman et al., 2015). Soybean has become one of the principal North American crops due to soybean's high yield capacity and easier harvest ability compared to other crops (Hartman et al., 2015).

## Soybean Production in the United States

Soybean has been an important crop in the United States (U.S) since the 1880s, when initially soybean's main use was for forage (Piper and Morse, 1923). Soybean production has increased rapidly in the United States since the 1950s (Qiu and Chang, 2010). Soybean production is grown in 22% of the approximately 137.6 million hectares of harvested cropland in the United States, second only to corn (CAST 2009; Lubowski et al., 2002). The main areas for soybean production in the US are the in the Midwest or Corn Belt, the Mid-South or Lower Mississippi River Delta, and the southeast or Atlantic Coast (CAST, 2009). In 2013, the United

States was the first soybean-producing country with 30.7 million ha planted and 89.5 million MMg harvested, which represented 31% of the total worldwide soybean production (Hartman et al., 2015). Around 30 to 40% of the soybeans produced in the US are exported (CES, 2019). According to the USDA, the total soybean-harvested area in 2019 in the US was 32.1 million ha, which is 4.2 million acres less than the area harvested in 2018 (USDA NASS, 2019). Illinois, Iowa, Minnesota, North Dakota, Indiana, Missouri, Nebraska, Kansas, South Dakota, Ohio, Arkansas, are the top 11 soybean-producing states in the US respectively (Table 1; NASS, 2019).

In the US, tillage is a common management practice to prepare soil for soybean planting. Conventional tillage means little to no residue is left on the soil after tillage and before planting (CAST, 2009). Soils are typically first tilled with primary tillage implements, such as moldboard plows, heavy disks, and chisel plows, and frequently more than once with a secondary tillage implement, such as a tandem disk harrow or field cultivator. In 2002, around 17% of soybeans in the United States were grown using a conventional tillage system (CAST, 2009). However, reduced tillage systems have gained popularity, which use only the secondary tillage implements (i.e., no moldboard or deep plowing), which tends to leave 15 to 30% of the soil covered with plant residues after tillage (CAST, 2009). In Arkansas, Louisiana, Mississippi, and Texas, soybean is commonly grown in rotation from year to year with rice (Koenning et al., 1999). In the Lower Mississippi River Valley, soybean is also frequently grown as a double-crop system in rotation with wheat over the winter months (i.e., November to May) (Brye et al., 2018).

## Soybean Production in Arkansas

In 2019, Arkansas was the 11th largest soybean-producing state in the U.S. (USDA NASS, 2019, Table 1) and the 45$^{th}$ globally (USDA NASS, 2019). Soybeans rank number one out of the three major crop commodities (i.e., soybean, rice, and corn USDA NASS, 2019) and are planted in 41 of the 75 counties in Arkansas (CES, 2019). In 2018, 83% of the 1,327,368 soybean hectares planted were irrigated and 17% of soybean production was non-irrigated (USDA NASS, 2019). The average state soybean yield under irrigated systems is 3,618 and 2,448 kg ha $^{-1}$ under non-irrigated systems, respectively (USDA NASS, 2019). In 2018, the 4,224,941 Mg harvested had a value of $1,49 billion (USDA NASS, 2019).

In Arkansas, most soybeans varieties are planted between April 25 to early June 30, but in northern Arkansas soybean MG IV can be planted before April 1 and before April 15 in northern Arkansas (Ashlock et al., 2019). Crop rotation increases soybean yields because the life cycle of many diseases and pests is broken (Ashlock et al., 2019). In Arkansas, wheat is most commonly grown in rotation with soybean. The common agronomic management practices for the wheat-soybean, double-crop production systems consist of N fertilization of the wheat in the spring of the year to optimize wheat grain yield followed by residue burning and conventional tillage after wheat harvest with soybean grown under irrigation (Brye et al., 2018).

**Non-weed Pests in Soybeans**

Diseases and pests on soybean plants are vital due to the importance of the crop (Hartman et al., 2015). Many soybean diseases were recognized more than 100 years ago, and others are relatively new (Hartman et al., 2015). As soybean is being grow in new territories, new pests and diseases will invariably appear (Hartman et al., 2015). Biotic and abiotic factors can cause diseases in plants. With biotic factors, the disease is transmitted from an infected plant to a healthy plant and the infection occurs when certain conditions are favorable (Hartman et al., 2015). Diseases in plants can be attributed to bacterial, viral, fungal infections, nematodes, and other parasitic plants (Hartman et al., 2015). More than 200 diseases can affect soybean growth and seed production (Hartman et al., 2015). However, only about 35 diseases have a major economic impact on soybean production (Hartman et al., 2015). Various soybean pathogens and pests can stay in soybean plants wherever soybeans are planted (Hartman et al., 2015). All the soybean plant parts are susceptible to diseases and pests, which can negatively affect soybean plant quality and production quantity (Hartman et al., 2015). The type of pathogen, plant development stage, severity of the disease on a single plant, and number of plants affected are the major factors affecting the degree of pest-caused damage to a plant.

## Non-weed Pests in Soybeans around the World

The most common diseases for soybean in Argentina, Brazil, and the US are brown spot (*Septoria glycines*), soybean rust (*Phakopsora meibomiae* and *P. packyrhizi*), and SCN, respectively (Hartman et al., 2015). In 2006, diseases caused the loss of approximately 59.9 MMg of soybean yield in the eight major soybean-producing countries, United States, Brazil, Argentina, India, China, Paraguay, Canada, and Ukraine (FAO, 2019). Of the 213.1 MMg of soybean yield produced in the eight leading countries, 28% of the yield was lost due to soybean diseases (Hartman et al., 2015). It was estimated that 13.6 MMg of soybean yield was lost in total in the US, Brazil, and Argentina combined (Hartman et al., 2015).

### *Non-weed Pests in Soybeans in Argentina*

In Argentina, an estimated of 40 diseases affect soybeans in Argentina (Hartman et al., 2015). Diseases such as downy mildew (*Peronospora manshurica*), frogeye leaf spot (*Cercospora sojina*), soybean rust , target spot (*Corynespora cassiicola*), Phytophthora root rot

(*Phytophthora sojae*), stem rot (*Phialophora gregata*), fusarium root rot (*Fusarium solani*), damping-off (*Pythium ultimum* Trow ), rhizoctonia root rot (*Rhyzoctonia solani)*, Sclerotium blight (*Sclerotium rolfsii*), charcoal rot (*Macrophomina phaseolina*), soybean mosaic virus (SMV), and nematodes affect soybean production in Argentina (Hartman et al., 2015). SNC, peanut root-knot (*Meloidogne arenaria*), and southern root-knot nematode (*Meloidogyne incognita*) are the most important nematodes that affect soybean production in Argentina. Cyst nematode caused problems in the 1990s, but, by the 2000s, soybean nematode populations decreased (Hartman et al., 2015). Integrated pest management practices and crop rotations were implemented to avoid pests and diseases. However, conservation tillage practices that are used to protect soil from erosion, conserve water, and improve physical and chemical soil characteristics can also harbor disease-causing pathogens over winter and promote negative disease effects in the subsequent crop (Hartman et al., 2015). Using certified seeds that are pathogen-free can decrease diseases on soybeans in Argentina (Hartman et al., 2015).

*Non-weed Pests in Soybeans in Brazil*

In 2013, Brazil planted 27.9 million ha of soybeans and harvested 81.7 MMg (Hartman et al., 2015). The development of cultivars adapted to low latitudes helped Brazil to become one of the worldwide leaders in soybean production (Hartman et al., 2015). Soybean rust, frogeye leaf spot, and southern stem canker (*Diaporthe phaseolorum*) were important diseases before the development of disease-resistant cultivars in Brazil (Hartman et al., 2015). In the-mid 1990s, stem canker caused soybean yield losses up to 100% in Brazil (Hartman et al., 2015). Soybean cyst nematode, lesion nematode (*Pratylenchus* spp.), reniform nematode, southern root-knot nematode, and javanese root-knot nematode (*Meloidogyne javanica*) were the most injurious to soybean production in Brazil (Hartman et al., 2015). Soybean cyst nematode was detected in the early 1900s and, by 2015, SCN had affected 3 million ha of soybeans (Hartman et al., 2015). Rotating soybeans with a non-host crop, particularly corn, and the use of genetically modified, disease-resistant cultivars helped to control nematode damage to soybean crops in Brazil (Hartman et al., 2015). However, the genetic variability of nematodes remains a problem (Hartman et al., 2015). In Brazil, lesion nematode is a major problem, particularly in sandy soils, and reniform nematode is a major problem in soybean-cotton (*Gossypium hirsutum*) rotations (Hartman et al., 2015).

*Non-weed Pests in Soybeans in Canada*

In Canada, soybean has been cultivated since the 1900s (Hartman et al., 2015). In 2013, 1.83 million ha of soybeans were grown and 5.2 MMg of soybeans were harvested (Hartman, 2015). Approximately 40 diseases affect soybean plants in Canada (Hartman et al., 2015). In Canada, SCN is the most important yield-limiting pest and causes major economic losses. Sudden death syndrome (*Fusarium virguliforme*), Sclerotinia stem rot (*Sclerotinia sclerotiorum* (Lib)), pod and stem blight [*Diaporthe phaseolorum* (Cke. & Ell.) Sacc. var. *sojae*], Phomopsis seed decay (*Phomopsis longicolla* T.W. Hobbs), and Phytophthora root (*Phytophthora sojae*) are other important diseases in Canada (Hartman et al., 2015).

The factors of disease occurrence are environmental conditions, susceptibility of the crop, and tillage practices (Hartman et al., 2015). In Canada, minimum tillage has had increased root diseases due to pathogens over-wintering in the crop residue left on the soil surface under reduced tillage. In addition, shorter crop rotations have increased soybean disease incidence (Hartman et al., 2015). Early cyst nematode detection and education are two activities that can help control nematode infestation (Hartman et al., 2015).

### *Non-weed Pests in Soybeans in China*

Soybean was cultivated in China hundreds of years ago (Hartman et al., 2015). In 2013, 6.6 million ha of soybeans were planted in China and 12.5 MMg of soybeans were harvested (Hartman et al., 2015). More than 30 diseases affect soybeans in China (Hartman et al., 2015). The most important diseases in China are bacterial blight (*Pseudomonas syringae* pathovar. *glycinea*), bean pod mottle (BPMV; genus *Comovirus*), brown spot, brown stem rot, downy mildew, frogeye leaf spot, Phytophthora root and stem, pod, and stem blight, rhyzoctonia root rot, sclerotinia stem rot, SCN, soybean mosaic virus, and soybean rust (Hartman et al., 2015). In China, eight different types of SCN have been reported. Soybean cyst nematode is a destructive pest in China (Hartman et al., 2015). In China, since the 1970s, thousands of soybean accessions have been studied for cyst nematode resistance (Hartman et al., 2015). The majority of resistant cultivars have brown or black seeds (Hartman et al., 2015). Crop rotation, management of soil fertility, and coating soybean seeds with a biocontrol (i.e., a fungus and/or bacteria) or nematicide (Hartman et al., 2015).

### *Non-weed Pests in Soybeans in India*

In 2013, India was the fourth largest soybean producer in the world. In the same year, 12.2 million ha of soybeans were planted and 11.9 MMg of soybeans were harvested. In the early years of soybean cultivation in India, there were no disease problems (Hartman et al., 2015). Approximately 35 diseases occur frequently in India (Hartman et al., 2015). Frogeye leaf spot, soybean rust, Mycrothecium leaf spot (*Myrothecium roridum*), brown spot, Alternaria leaf spot (*Alternaria* spp.) pods and stems anthracnose (*Colletotrichum truncatum*), cercospora leaf blight (*Cercospora kikuchii*), rhizoctonia aerial blight (*Rhizoctonia solani* AG1-1A,), pod blight (*Alternaria, Myrothecium, Macrophomia phaseolina*), purple seed stem (*Cercospora kikuchii*), fusarium blight (*Fusarium tracheiphilum*), fusarium pod and collar rot (*Fusarium* spp.), target leaf spot, choanephora leaf blight (*Choanephora infundibulifera*), phoma leaf blight (*Phoma* sp), phyllosticta leaf spot (*Phyllosticta sojicola*), bacterial pustule (*Xanthomonas phaseoli*), yellow mosaic disease (YMD), and nematodes are the principal soybean diseases in India (Hartman et al., 2015). In India, nematodes have not been studied extensively yet, but a population between 300 to 500 root-knot and reniform nematodes can exist in 250 g of moist soil (Hartman et al., 2015).

*Plant-parasitic Nematodes in the US*

In 2013, the US was the top soybean-producing country with 30.7 million ha of soybean planted and 89.5 MMg of soybean grain harvested, which represented 31% of the total worldwide soybean production (Hartman et al., 2015). Soybeans are grown in 37 states in the US and diseases occur in all the areas where soybeans are produced (Hartman et al., 2015). In the Us and Ontario an average of $ 60.66 USD per acre is estimated to be the soybean economic losses caused by diseases (Allen et al., 2017) The annual average yield loss attributed to soybean diseases is approximately 11% in the US (Hartman et al., 2015). An annual average of 11.2 MMT or 13% of the total soybean grain yield in the US were lost during the 2006 to 2009 period from diseases (Hartman et al., 2015). The principal pest that affects soybean in the US is SCN, which accounted for 30.9% of the total loss during the 2006 to 2009 period (Hartman et al., 2015).

Soybean cyst nematode is the most important pest for soybean production in the US (Hartman et al., 2015; Young, 1996). The first article written by S. Hori documented the SCN damage to soybeans in Japan in 1915 (Davis and Tilka, 2000). However, in China, old Chinese personal reports and other texts suggest that SCN has been a soybean pathogen since as early as 235 BCE (Davis and Tilka, 2000). The first report of SCN in the US was in 1954, in Hanover County, North Carolina, an area known for importing bulb flowers from Japan (Hartman et al., 2015 and Davis and Tilka, 2000). The rapid SCN spread to other soybean-growing states suggests that SCN is native to many areas and parasitizes some weeds and legumes in the US (Davis and Tilka, 2000). There are some reports that soybean seeds had been imported to the US earlier than 1765. Lambert and Bekal (2002) mentioned that SCN may have been introduced to the US in soil to obtain rhizobia (*Bradyrhrizobium japonicum*) imported from Asia and distributed to soybean researchers.

Root-knot nematode is the second most detrimental nematode in soybean production (Hartman et al., 2015). However, the importance of lance, lesion, reniform, and sting nematodes have not been well-studied yet in the US (Hartman et Al., 2015). Moreover, lance nematode, lesion nematode, Reniform, and Dagger nematode are major plant-parasitic nematodes to cause crop losses (Koenning et al., 1999).

## Plant-parasitic Nematodes in Soybeans

More than 100 nematode species have been related to soybean roots, but only a few of them are economically important (Hartman et al., 2015). Plant-parasitic nematodes potentially cause agronomic and economic losses in the wheat-soybean, double-crop production systems in the Mid-Southern US (Brye et al., 2018). Farmlands infected with nematodes often have low productivity and weed problems because palmer pigweed (*Amaranthus palmery*), redroot pigweed (*Amaranthus retroflexus*), spiny pigweed (*Ama*ranthus *spinosus)*, sicklepod (*Senna obtusifolia*), common lambsquartes (*Chenopodium album*), field bindweed (*Convolvulus arvensis*), yellow nutsedge (Cyperus esculentus L), purple nutsedge,(*Cyperus rotundus*) morning glory (*Ipomoea purpurea*), henbit (*Lamium amplexicaule*), nightshade (*Solanum* sp), common ragweed (*Ambrosia artemisiifolia*), barnyard grass (*Echinochloa crus-galli*), and goosegrass (*Carex* sp.) are suitable hosts for SCN. Nematode management is challenging to manage due to the difficulty to target the nematodes with the pesticides to the soil (ASPB, 2019).

Soybean cyst nematode continues to be the main constraint on soybean production (Bao et al., 2011). Infected soybean plants do not always present typical symptoms of nematode infection, such as chlorosis and stunting, and some fields infested with nematodes may or may not present foliar symptoms at all (Hartman et al., 2015). In Tennessee, on a Lexington silt loam (fine-silty, mixed, active, thermic Ultic Hapludalfs) SCN caused soybean yield losses in the absence of visual symptoms on above-ground plant material (Young, 1996).

**Plant-parasitic Nematodes in Arkansas**

Between 1978 and 1986, the most important parasitic nematodes in Arkansas were SCN, stunt nematode, northern root lesion nematode, spiral nematode (*Helicotilenchus pseudurobustus*), stunt nematode (*Tylenchorhynchus ewingi*), and American dagger nematode (*Xiphinema americanum*) (Robbins et al., 1987). Moreover, smooth-headed lesion nematode (*Pratylenchus brachyurus*), walnut root-lesion nematode (*P. vulnus*), corn root-lesion nematode (*P. zeae*), stunt nematode (*Tylenchorhynchus* canalis and *T. goffarti)*, rice stunt nematode (*T.*

*martini*), steiner's spiral nematode (*Helicotylenchus dihystera*), yam nematode (*Scutellonema bradys*), chamber's dagger nematode (*Xiphinema chambersi*), rivesi dagger nematode (*X. rivesi*),cobb's lance nematode (*Hoplolaimus galeatus*), lance nematode (*H. magnistylus*), stubby root nematode (*Paratrichodorus minor* and *P. christiei*), pin nematode (*Paratylenchus projectus* and *P. tenuicaudatus*), ring nematode (*Mesocriconema* spp*)*, and stunt nematode (*Meiodorus hollisi*) are other soybean parasitic nematodes in Arkansas (Robbins et al., 1987). In 1979, reniform nematode was first reported in Arkansas, specifically in a soybean field in Crawford County (Robbins et al., 1987). In Arkansas, in 1979, nematode infestation in soybean was mainly caused by SCN (77.7% of infestation), root-knot nematode (7.2% of infestation), lesion (56.0% of infestation), stunt (33.8% of infestation), spiral (33.1% of infestation), dagger (20.9% of infestation), stubby-root (15.1% of infestation), pin (8.6% of infestation), lance (2.2% of infestation), ring (< 1%), and others (1.4% of infestation) (Robbin et al., 1987).

Kirkpatrick (2017) reported that in Arkansas 28%, of soil samples tested positive for the Southern RKN and SCN nematode, 20% to lesion, and 2 % to reniform nematode. The SCN has been a serious concern in Arkansas for the last 30 years; the Southern RKN and the reniform nematode is a relatively new reported to cause soybean damage in the last 20 to 30 years (Kirkpatrick, 2017). Soybean yield losses have been associated to the Southern RKN, but the impacts of lesion and reniform nematode are still unknown (Kirkpatrick, 2017).

**Economic Losses Caused by Nematodes**

Nematodes cause yield losses in soybeans and other crops around the world. In the U.S., SCN damage accounted for 30.9% of the total soybean yield losses during the 2006 to 2009 period (Hartman et al., 2015). In the U.S., SCN causes more than $1 billion in crop damage every year

(Wrater and Koenning, 2006). The Southern root-knot nematode hinders the production of many crops around the world (Allen et. al., 2017). In 1994, SCN caused soybean yield losses of 1 to 5% in Arkansas (Arkansas Soybean Promotion Board, 2019). More recently, in the 28 U.S. soybean-producing states and Ontario, Canada, SCN alone caused more than 16, 803 thousand Mg in yield losses from 2010 to 2014 (Allen et. al., 2017).

**Plant-parasitic Nematode Control**

The use of resistant cultivars, nematicides, and rotations with a non-host crop are the main tactic used to control SCN (Bao et al., 2011). In the U.S. exists hundreds of soybean cultivars that are resistant to more than one race of SCN, but there is not agronomically accepted soybean cultivars for many races of SCN (Bridge and Starr, 2007). Moreover, no soybean cultivar is resistant to root-knot nematode, reniform, and SCN when all together are present in the soil (Thomas, 1994). However, there are moderately resistance to RKN in some MG 4 soybean cultivars (Delta Grow DG 4995 GLY, Delta Grow DG 4940, Pioneer P47T59R, and Terral REV48A46) (Emerson et al, 2018). Nematicides are efficient control measures for nematodes, but economic and environmental problems are of concern (Rich et al., 2004). Using a combination of resistant cultivars and crop rotation is the most effective and universally practiced strategy for managing soybean pests (CAST, 2009). It has been suggested that soybeans should not be rotated with corn and cotton when the southern root-knot nematodes are present because corn and cotton are suitable hosts for the southern root-knot nematode; however, if a field is infested with SCN or reniform nematode, corn should be planted in rotation with soybeans as corn is a non-host for SCN and reniform nematode. In addition, rice can be planted in rotation with soybeans, which is a common crop rotation in Arkansas as flooded rice can be a good management tool for southern root-knot nematode; however, SCN eggs can survive in cyst even when flood is maintained during the cropping season in a rice field.

## Research Studies on Nematodes

### World Wide

In France, a 14-year-long study on a Luvisol soil (silt-loam texture) in which winter wheat was planted each year concluded that conservation and organic agriculture increased the total nematode population from 100 to 700%, but decreased the population of predaceous nematodes (Henneron et al., 2015). Specifically, the total nematode population increased by a factor of seven under long-term, no-tillage (NT) systems (Henneron et al., 2015). In Nigeria, spiral nematode and root knot nematode juvenile populations were smaller under a corn rotation with other crops and NT than under conventional tillage (CT) (Caveness, 1979).

### United States

*Tillage Effects*

In the U.S., 25.1 million hectares were under NT systems in 2018 (USDA-NRCS, 2019). In the U.S., little is known about the effects of tillage and cropping systems on different species of nematodes (Cheng et al., 2018). However, many studies have reported the effects of tillage on SCN (Bao et al., 2011). In Michigan on a Sisson sandy loam soil (fine, loamy, mixed, semiactive, mesic Type, Hapludalfs), plant-parasitic nematode population density was significantly lower in tilled compared to no-tilled treatments 157 days after planting in 2019 (Cheng et al., 2018). In the north-central U.S., inconsistent tillage effects were observed on SCN population (Bao et al., 2011). Hershman and Bachi (1995) reported that on a wheat-soybean double-crop study conducted from 1990 to 1992 in Kentucky on a Crider silt loam (fine-silty, mixed, active, mesic Typic Paleudalfs), and on a Pembroke silt loam soil (fine-silty, mixed, active, mesic Mollic Paleudalfs), SCN eggs population density was numerically larger under minimum-tillage than NT at soybean planting, but the results were the opposite at harvesting in 1992. In South Carolina, the population densities of root knot nematode and stubby-root nematode remained stable under minimum tillage and CT corn (i.e., mono-crop system) (Fortum and Karlen, 1985). In Georgia, on a Marlboro sand (fine, kaolinitic, thermic Typic Paleudults), lance nematode population densities were greater at 20 to 33 and 33 to 46 cm depths in sub-soiled soybean than CT soybeans; however, the total number of plant-parasitic nematodes in sub-soiled and CT systems were the same (Parker et al., 1975). In Tennessee, on a Lexington silt loam soil SCN population densities in soybean was lower under NT compared to other tilled systems, such as disked, chiseled, sub-soiled under rows, and sub-soiled between rows (Tyler et al., 1983). Moreover, in Indiana, on a silt loam soil, densities of lesion nematode in soybean were greater under CT than in under zero-tillage, which was attributed to the larger and robust soybean roots under CT (Alby et al., 1983). In Georgia, on a sandy clay loam soil plant-parasitic nematode population in a grain sorghum (*Sorghum bicolor*)-cereal rye (*Secale cereale*) rotation were reduced with NT than CT (Stinner and Crossley, 1982).

Since the nematode life cycle is relatively short, nematode population densities and degree of plant damage can vary throughout the soybean growing season. Baird and Bernard (1984) studied nematode population and community dynamics in soybean-wheat cropping and tillage regimes in Tennessee. The study concluded that in July SCN J2 population densities were greater under CT, soybean single-crop system compared to CT wheat-soybean double crop, CT after aerially seeded wheat, soybean NT after CT wheat, and soybean NT after aerially seeded wheat (Baird and Bernard, 1984). In Iowa, on a Clarion-Nicollet-Webster loam soil (fine-loamy, mixed, superactive, mesic Typic Hapludolls, fine-loamy, mixed, superactive, mesic Aquic Hapludolls, and fine-loamy, mixed, superactive, mesic Typic Endoaquolls) with 40 to 50% sand, plant-parasitic nematodes in a monoculture corn crop were more abundant in NT plots than in spring- and autumn-tilled plots (Thomas, 1978). Pin nematode population increased during the corn growing season under a variety of conventional and conservative tillage treatments (Thomas, 1978). Plant parasitic nematodes formed aggregation under single-cropped soybean-CT; however, plant parasitic nematodes did not form aggregation in all double-cropped systems (Baird and Bernard, 1984). In Indiana, in a silt loam soil, the population of lesion nematode was more uniformly spatially distributed in non-tilled than in tilled soybean plots (Alby et al., 1983). In Georgia, on a Marlboro sand soil lance nematode population density in the top 20 cm was greater under a monoculture soybean crop with no sub soiling than when sub-soiled was imposed (Parker et al., 1975). In addition, the lance nematode population decreased with soil depth (Parker et al., 1975). In South Carolina, sub-soiling and nematicides were effective control of lance nematodes (Blackmon and Musen, 1974). Given the variation in nematode response to tillage in these studies the effect of tillage practices varies greatly among nematode types and soil types across the U.S.

*Crop Rotation and Cover Crops Effects*

Multi-crop rotations may increase or decrease nematode issues depending on the crop in rotation (Minton, 1986). Farming resistant or susceptible soybean cultivars for 7-years under CT or NT in rotation with corn on a Drummer silty clay loam with 6% SOM had no long-term influence on SCN egg density (Noel and Wax, 2003). However, in non-tilled systems in rotation with corn, the number of eggs produced was greater at harvest than at planting (Noel and Wax, 2003). In southern U.S a 6-year study on a Tifton loamy sand (fine-loamy, siliceous, thermic Plinthic Kandiudults) with 0.5% soil organic matter (SOM) concluded that the population densities of the southern root knot nematode and peanut root-knot nematode did not increase over time under crop rotations of wheat, peanut (*Arachis hypogaea*), and cotton under minimum tillage and sprinkler irrigation (Johnson et al., 2000). In a wheat-soybean double crop on a Lexington silt loam soil in Tennessee under five CT systems (i.e., disking, chisel plowing, moldboard plowing, between-row sub-soiling, and under-row sub-soiling) followed by disking and/or section harrowing, using conventional to NT planting, where the cover crop (wheat) was chemically killed, the SCN population was lower under non-tilled than under CT treatments (Tyler et al., 1987). A 3-year corn-soybean rotation, the populations of SCN, stubby-root nematode, and sting nematode increased over time under rip-plant corn (Minton et al., 1986). In Illinois, a 5-year study  on four different soils, Proctor silt loam (fine-silty, mixed, superactive,mesic Typic Argiudolls), Cisne silt loam (fine, smectitic, mesic Mollic Albaqualfs) (light-colored), Drummer clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquolls), and a clay loam soil (dark-colored), with rotations including corn, soybean, wheat, and a forage crops alfalfa, red clover (*Trifolium pratense*), and Bomegras (*bromus inermis*), population densities of spiral nematode and stylet-stunt nematode were greater in dark-colored than in light-colored soils, while pin nematode population density was favored in the light-colored soils (Ferris and Bernard, 1971). Dagger nematode population density was not affected by crop and soil type, but the population densities of lesion nematode species were low in all the treatments (Ferris and Bernard, 1971). Crop rotation can decrease nematode population when a non-susceptible cultivar is planted in the crop rotation.

*Soil Moisture/Irrigation Effects*

Soil moisture content can affect nematode populations. In irrigated soils (i.e., large water contents) in North Carolina, nematode population densities were lower than in non-irrigated soils (i.e., low water contents; Koenning and Barker, 1995). The greater SCN population density under no irrigation may be because of a more favorable soil water/oxygen content ratio (Koenning and Barker, 1995). In irrigated sand, sandy loam, and muck soils, SCN damage increased, and soybean yield decreased; however, SCN did not affect soybean yield in non-irrigated, fine-textured soils (Koenning and Barker, 1995). In soybean, supplementary irrigation cannot be applied with the purpose of controlling nematode populations or damage (Koenning and Barker, 1995).

Soil moisture affects primarily soybean growth and yield potential. Likewise, soil matric potential influences plant parasitic nematode's capacity to hatch, to move in the soil, detect and penetrate a host plant, and mate (Koenning and Barker, 1995). In dry conditions, soybean plants respond to moisture by extending root biomass that may favor SCN reproduction (Heatherly et. al., 1992). A study conducted in a greenhouse using either Dubbs silt loam (fine-silty, mixed, active, thermic Typic Hapludalfs) or Sharkey clay (very fine-silty, montmorillonitic, nonacid thermic Vertic Haplaquept) concluded that reproduction of SCN was greater at -20 to -40 than at -60 to -80 kPa (Young and Heatherly, 1988). In a Vicksburg sandy loam (coarse-silty, mixed, active, acid, thermic Typic Udifluvents), -30 to -40 kPa was the ideal soil matric potential range for SCN reproduction (Heatherly et al., 1982). In another greenhouse study using a Dubbs silt-loam soil, SCN population densities increased overtime (3 years) in the irrigated treatment that maintain an optimum water potential (i.e., -30 kPa), but SCN population densities remained stable and similar to the initial infestation in the soil that was irrigated at half the rate to maintain an optimum water potential (i.e., dry soil) (Heatherly and Young, 1991). However, the SCN population densities decreased over time in both the wet and dry clay-soil treatments (Heatherly and Young, 1991). Root-knot nematode and sugar beet cyst nematode (*Heterodera schachtii*) eggs hatched evenly at field capacity (-10 to -33 kPa) and permanent wilting point (-20 to –50 kPa); however, the hatched nematodes were not able to migrate in the soil at permanent wilting point (Couch and Bloom, 1960; Wallace, 1955). Water distribution in the soil pores is an important aspect for the movement of sugarbeet nematode juveniles (Wallace, 1958a, b). Soybean cyst nematode J2 became inactive for a long period of time and survived in water up to 630 days; however, freezing did not kill nematodes immediately (Slack et al., 1972).

*Nitrogen Fertilization Effects*

Urea (46-0-0; N-P-K), has been investigated as a potential nematicide because ammoniacal N is harmful to nematodes (Rodriguez-Kabana, 1986). A nematode population can be effectively suppressed using mineral fertilizers containing ammoniacal N because ammoniacal-based N fertilizers tend to be toxic to nematodes. (Rodriguez-Kabana, 1986). The use of anhydrous ammonia reduced populations of tobacco stunt nematode (*Tylenchorhynchus claytoni*), Steiner's spiral (*Helicotylenchus dihystera*), and SCN more than the application of 150 kg N ha$^{-1}$ as urea. However, applying urea above 350 kg N ha$^{-1}$ can control many nematodes, including root-knot nematode (Rodriguez-Kabana, 1986). Different C:N ratios of organic fertilizers can also affect nematode populations, where greater N concentrations in the soil tend to decrease the nematode population (Rodriguez-Kabana, 1986). Mojtahedi and Lownsbery (1976) conducted an in-vitro study in which nematodes (ring nematode) were controlled with fertilizer that generate $NH_3$ (ammonia). Though urea has been shown to successfully control nematode populations when applying more 300 kg N per kg soil (Huebner, et al. 1983; Rodríguez-Kábana, 1986), large N fertilization rates can result in phytotoxicity (Huebner, 1983; Rodríguez-Kábana, 1986). Different nematode species are affected by different fertilizer doses. For instance, inhibited the population densities of lesion nematode and lance nematode, but did not affect that of stunt nematode (Miller, 1976). The application of N-containing organic fertilizers to the soil has also been shown to reduce nematode populations (Rodriguez-Kabana, 1986).

*Residue Burning Effects*

Little research exists on the effects of burning on nematodes in agricultural soils. However, some studies have addressed the effects of burning on nematodes in forests and prairies. Cerevkova et al. (2013) examined short-term effects of forest disturbances on soil nematode communities in a spruce (*Picea* spp.*)* forest in Slovakia during June and October of 2006 to 2008 on a cambisol podzolic soil with pH of 4.0 at the 10-cm soil depth under annual forest burning, in which a total of 46 species of nematodes were recorded after three years of the annual burning. Of the 46 nematodes recorded, the majority were bacterial feeders and nine were plant parasites (i.e., spiral, pin, reniform, and stubby root-knot nematode species) (Cerevkova et al., 2013). The researchers reported that the total nematode population densities decreased by 34.5% and 50.6% in 2007 and 2008 compared to 2006, respectively; however, the diversity of nematode species increased by 13% from the first to third year of the study, where burning was imposed each year (Cerevkova et al. 2013). The abundance of bacterial-feeding nematodes decreased by 53.9%, root-fungal feeders decreased by 44.6%, omnivores decreased by 68.4%, and insect parasites decreased by 53.9% from 2006 to 2008, respectively (Cerevkova et al., 2013). In contrast, the plant-parasitic nematode population increased by 70.3% from 2006 to 2007, but then decreased by 55.1% from 2007 to 2008 (Cerevkova et al., 2013). In addition, the population densities of predator nematodes increased 71% from the first to the last year of the field experiment (Cerevkova et al., 2013). The annual burning treatment in this forest affected the nematode population according to the species and/or their feeding habits (Cerevkova et al., 2013).

A study conducted in Iowa evaluated the effects of annual burning on nematodes from 1997 to 2004 in an oak (*Quercus* spp.) forest on a Tama soil series (fine-silty, mixed, superactive, mesic Typic Argiudolls), in which long-term burning and non-burning treatments were imposed (Fenster et al., 2004). Results of this study showed that nematode population densities did not differ between the burn and no-burn treatments (Fenster et al., 2004).

Another study evaluated the effects of management practices on a nematode community in a prairie on an Irwin silty-clay-loam soil series (fine, mixed mesic, Pachic Argiustoll), with big bluestem (*Andropogon gerardii*), Indiangrass (*Sorghastrum nutans*), and switchgrass (*Panicum virgatum* L.) as the prevalent vegetation, in which annually burning and non-burning treatments were applied (Todd, 1996). Under the burn and no-burn treatments, spiral nematode populations at the 20-cm soil depth were 137% greater under the annually burned compared to the unburned treatment after nine years of management (Todd, 1996), which may be due to the increase of forbs (*Sambucus canadensis*) and decrease of in C4 grasses (*Aristida*, *Stipagrostis*, *Paspalum*, *Panicinae* genus, etc) under the no burn, unmowed and N fertilize plots (Gibson et. al. 1993). In addition, pin nematode population densities under the burn treatment were 17 to 97% lower in the burn-mow compared to unburned-unmowed treatment combination (Todd, 1996). Based on results of these few studies evaluating the effects of burning on nematodes, it appears that burning may positively or negatively influence nematode populations in the soil.

**Relevant Research in Arkansas**

There is a little research on nematodes as affected by agricultural practices in Arkansas. In Fayetteville, Arkansas, susceptible soybean cultivar growth in a Captina silt-loam soil (fine-silty, siliceous, active, mesic Typic Fragiudult) in a large pot experiment with three water regimes (i.e., -30 kPa, -50 kPa, and no irrigation), SCN population increased under non-irrigated conditions (Johnson et al., 1994). However, SCN had no impact on soybean growth under the three irrigation systems (Johnson et al., 1994). In Arkansas, the largest population densities of reniform nematode were observed in soils with 54 to 60% silt content (Monfort et al., 2008). Brye et al. (2018) studied the effects of agricultural management practices in a wheat-soybean, double-crop production system in eastern Arkansas on a Calloway silt-loam soil (fine-silty, mixed, thermic, Glossaquic Fragiudalfs). The study was conducted during the 2016 soybean growing season, 15 years after the long-term study began, in which the combined effects of tillage (CT and NT), irrigation (Irrigated [I] and non-irrigated [NI]), residue level (high-[H] and low-[L]), and burning (burned-[B] and non-burned-[NB]) treatments were applied to evaluate nematode populations and long-term treatments effects. (Brye et al., 2018). Results of the study showed that the SCN J2 population density was four times greater under the non-burned-irrigated compared to the burned-non-irrigated treatment combination 70 days after planting (Brye et al., 2018). Moreover, the stunt and total nematode populations were almost three times greater under a burn-non-irrigated-NT than under a burn-non-irrigated-CT treatment combination 34 and 70 days after planting, respectively (Brye et al., 2018). Lance nematode populations were one time and three times greater under a burn-non-irrigated-NT than under a burn-non-irrigated-CT treatment combination 34 and 70 days after planting, respectively (Brye et al., 2018). The concentration of SCN eggs were eight times greater under no-burn-irrigated than under the burn-non-irrigated treatment combination 34 days after planting (Brye et al., 2018).

## Justification

Soybean is the most important commodity crop in the U.S., as soybeans are an essential part of the diet of millions of people, cattle, and poultry, and source material for industry (i.e., oil). As the human population in the world increases, soybean production will likely also have to increase to satisfy the demand for adequate food production. However, nematodes are one of the main pest management constrains in soybean production in the U.S., particularly in Arkansas, where the soybean industry provides many jobs and greatly contributes to the state economy. However, there has been no research in Arkansas characterizing the long-term effects of the combination of different tillage (conventional tillage and no tillage), water management (irrigation and non-irrigation), and residue management (burned and non-burned) practices on plant-parasitic nematodes in soybean. It is necessary to determine whether or not different tillage, water management, and residue management systems negatively or positively influence nematode populations.

## Objective

The objective of this study was to evaluate the combined long-term effects of tillage practice (conventional tillage and no tillage), water management (irrigation and non-irrigation), residue burning (burned and non-burned), and wheat residue level (high and low) on plant-parasitic nematode population densities and reproduction in the top 10 cm within the growing season and between years soybean in a double-crop production system on a silt-loam soil in eastern Arkansas.

## Testable Hypotheses

For this research, there are several hypotheses related to the management practices in soybean production in eastern Arkansas. One hypothesis is that greater nematode (root-not, SCN, reniform, spiral, lance, stunt, dagger, lesion, ring, stubby-root) populations exist under conventionally tilled plots because nematodes are typically transported on contaminated equipment and plant parts, which may also increase nematode population. Also, due to that tillage increases soil porosity temporarily. It is also hypothesized that nematode populations are greater under irrigated conditions due to greater moisture levels, which nematodes require to move, live, hatch, and reproduce. Additionally, it is hypothesized that nematode population densities will be lower under the high- than the low-wheat-residue treatment due to the decomposition of organic matter, which suppresses microorganisms in the soil. It is also hypothesized that the nematode population will be greater in the non-burned compared to the burned treatment because of greater soil moisture conditions.

## Literature Cited

Alby, T., Ferris, J. M., and Ferris, V. R. 1983. Dispersion and distribution of *Pratylenchus scribneri* and *Hoplolaimus galeatus* in soybean fields. Journal of Nematology 15:418-426.

Allen, T. W., Bradley, C. A., Sisson, A. J., Byamukama, E., Chilvers, M. I., Coker, C. M., Collins, A. A., Damicone J. P., Dorrance, A. E., Dufault, N. S., Esker, P. D., Faske. T. R., Giesler, L. J., Grybauskas, A. P., Hershman, D. E., Hollier, C. A., Isakeit, T., Jardine, D. J., Kelly, H. M., Kemerait, R. C., Kleczewski, N. M., Koenning, S. R., Kurle, J. E., Malvick, D. K., Markell, S. G., Mehl, H. L., Mueller, D. S., Mueller, D. J., Mulrooney, R. P., Nelson, B. D., Newman, M. A., Osborne, L., Overstreet, C., Padgett, G. B., Phipps, P. M., Price, P. P., Sikora, E. J., Smith, D. L., Spurlock, T. N., Tande, C. A., Tenuta, A. U., Wise, K. A., and Wrater, J. A. 2017. Soybean yield loss estimates due to diseases in the United States and Ontario, Canada, from 2010 to 2014. Plant Health Progress 18: 19-27.

Arkansas Soybean Promotion Board (ASPB). 2019. Controlling harmful effects of nematodes [Online]. Available at: https://www.themiraclebean.com/controlling-the-harmful-effects-of-nematodes-2/ (verified 25 Nov., 2019).

Ashlock, L., Klerk, R., Huitink G., Keisling, T., and Vories, E. Planting practices [Online]. Available at https://www.uaex.edu/publications/pdf/mp197/chapter7.pdf (verified 26 Nov., 2019).

Baird, S. M., and Bernard, E. C. 1984. Nematode population and community dynamics in Soybean-wheat cropping and tillage regimes. Journal of Nematology 16:379-386.

Bao, Y., Neher, D. A., and Chen, S. 2011. Effect of soil disturbance and biocides on nematode communities and extracellular enzyme activity in soybean cyst nematode suppressive soil. Nematology 13:687-699.

Blackmon, C. W., and Musen, H. L. 1974. Control of the columbia (lance) nematode *Hoplolaimus columbus* on soybeans. Plant Diseases 58:641-645.

Bridge, J., and Starr, J. L. 2007. Plant nematodes of agricultural importance: A colour handbook. Manson Publishing. London, UK.

Brye, K. R., Quarta, M., Morrison, C., and Rothrock, C. 2018. Long-term effects of residue and water management practices on plant parasitic nematode abundance and soybean root infection. Applied Soil Ecology 124:275-283.

Caveness, F. E. 1979. Nematode population under no-tillage management regime. Pp. 133-145 in R. Lal, ed. Soil tillage and crop production. International Institute of Tropical Agriculture, Ibadan, Nigeria.

Cheng, Z., Melakeberhan, H., Mennan, S., and Grewal, P. S. 2018 Relationship between soybean cyst nematode, *Heterodera glycines*, and soil nematode communities under long-term tillage and crop rotation systems. Nematropica 48:101-114.

Cerevkova, A., Renco, M., and Cagan, L. 2013. Short-term effects of forest disturbances on soil nematode communities in European mountain spruce forests. Journal of Helminthology 87: 376-385.

Cooperation Extension Center (CES). 2019. Soybean production in Arkansas. [Online]. Available at https://www.uaex.edu/farm-ranch/crops-commercial-horticulture/soybean/ (verified 12 Nov., 2019).

Couch, H. B. and Bloom, J. R. 1960. Influence of soil moisture stress on the development of the root knot nematode. Phytopathology 50:319-321.

Council for Agricultural Science and Technology (CAST). 2009. Sustainable of U. S. soybean production: Conventional, transgenic, and organic production systems. Ames, Iowa.

Davis, E. L., and Tilka, G. L. 2000. Soybean cyst nematode disease. The Plant Health Instructor [Online]. doi: 10.1094/PHI-I-2000-072501(verified 12 Sep., 2018).

Emerson, M. Brown, K. Faske, T.R., and Kirkpatrick T, L. 2018. Field performance of several glyphosate-resistant maturity group 4 and 5 soybean cultivars in a root-knot nematode infested field. Pp. 40-41 in J. Ross ed. University of Arkansas Research Studies 2016. University of Arkansas Experiment Station. Fayetteville.

Fehr, W. R., Cavinnes, C. E., Burmood, D. T., and Pennington, J. S. 1971. Stage of development descriptions for soybeans, Glycine max (L) Merrill. Crop Science 11:929-931.

Fenster, M., Ferrick, C., and Scott, M. 2004. Fall burning does not affect nematode density or carbon and nitrogen levels in Iowa oak forest soils. Tillers 5:9-12.

Ferris, V. R., and Bernard, R. L 1971. Effect of soil type on population densities of nematodes in soybean rotation fields. Journal of Nematology 3:123-128.

Fortum, B. A., and Karlen, D. L. 1985. Effects of tillage system and irrigation on population densities of plant nematodes in field corn. Journal of Nematology 17:25-28.

Food and Agriculture Organization of the United Nations (FAO). 2019. Top 20 countries, net production value of soybeans 2016 [Online]. Available at: http://www.fao.org/faostat/en/#rankings/countries_by _commodity (verified 26 Nov., 2019).

Fujimoto, T., Hasegawa, S., Otobe, K., and Mizukubo. 2010. The effect of soil water flow and soil properties on the motility of second-stage juveniles of the root-knot nematode (*Meloidogyne incognita*). Soil Biology and Biochemistry 42:1065-1072.

Gibson, D. J., Seastedt, T. R., and Briggs, J. M. 1993. Management practices in tallgrass prairie: large- and small-scale experimental effects on species composition. Journal of Aplied Ecology 30:247-255.

Hartman, G. L., Rupe, J. C., Sikora, E. J., Domier, L. L., Davis, J. A., and Steffey, K. L. 2015. Compendium of soybean diseases and pests. The American Phytopathological Society. St. Paul, Minnesota, U.S.

Heatherly, L. G., and Young, L. D. 1991. Soybean and soybean cyst nematode response to soil water content in loam and clay soils. Crop Science 31:191-196.

Heatherly, L. G, Young, L D., Epps, J. M., and Hartwig, E. E. 1982. Effect of upper-profile soil water potential on numbers of cysts of *Heterodera glycines* on soybeans. Crop Science 22:833-835.

Heatherly, L. G., Pringle, H. C., Sciumbato, G. L., Young, L. W., Ebelhar, M. W., Wesley, R. A., and Tupper, G. R. 1992. Irrigation of soybean cultivars susceptible and resistant to soybean cyst nematode. Crop Science 32:802-806.

Henneron, L. Bernard, L., Hedde, M., Pelosi, C., Villenave, C., Chenu, C., Bertrand, M., Cyril, G., and Blanchart, E. 2015. Fourteen years of evidence for positive effects of conservation agriculture and organic farming on soil life. Agronomy for Sustainable Development 35:169-181.

Hershman, D. E., and Bachi. P. R. 1995. Effect of wheat residue and tillage on *Heterodera glycines* and yield of double crop soybean in Kentucky. Plant Disease 79:631-633.

Huebner, R. A., Rodríguez-Kábana, R., and Patterson, R. M. 1983. Hemicellulosic waste and urea for control of plant parasitic nematodes. Effect on soil enzyme activities. Nematropica 13:37-54.

Johnson, A. W., Dowler, C. C., and Handoo, Z. A. 2000. Population dynamics of *Meloidogyne incognita, M. arenaria* and other nematodes and crop yields in rotations of cotton, peanut, and wheat under minimum tillage. Journal of Nematology 32:52-61.

Johnson, A. B., Scott, H. D., and Riggs, R. D. 1994. Response of soybean in cyst nematode-infested soils at three soil-water regimes. Journal of Nematology 26:329-335.

Joshi, T., Valliyodan, B., Wu, J. H., Lee, S. H., Xu, D., and Nguyen, H.T. 2013. Genomic differences between cultivated soybean, G. max and its wild relative *G. soja.* BMC. Genomics [Online]. doi: 10.1186/1471-2164-14-S1-S5 (verified 26 Nov., 2018).

Karssen, G. and Moens, M. 2006. Root-knot nematode. In Perry, R. N and Moens, M. (eds), *Plant Nematology* (pp. 60). Cambridge, MA: CABI.

Khan, M. R. 2008. Plant nematodes: methodology, morphology, systematics, biology and ecology. Science Publishers, Enfield, NH, U.S.

Kirkpatrick, T. 2017 Incidence, population density, and distribution of soybean nematodes in Arkansas. Pp. 72-74 in J. Ross ed. University of Arkansas Research Studies 2015. University of Arkansas Experiment Station. Fayetteville.

Koenning, S. R., and Barker, K. R. 1995. Soybean photosynthesis and yields as influences by *Heterodera glycines*, soil type, and irrigation. Journal of Nematology 27:51-62.

Koenning, S. R., Overstreet, C., Noling, J. W., Donald, P. A., Becker, J. O., and Fortnum, B.A. 1999. Survey of crop losses in response to phytoparasitic nematode in the United States for 1994. Journal of Nematology 31:587-618.

Lambert, K., and Bekal, S. 2002. Introduction to plant-parasitic nematodes. The Plant Health Instructor [Online]. doi: 10.1094/PHI-I-2002-1218-01 (verified 26 Nov., 2018).

Lubowski, R. N., Vesterby, M., Bucholtz, S., Baez, A., and Roberts, M. J. 2002. Major uses of land in the United States. EIB-14. U.S. Department of Agriculture-Economic Research Service, Washington, D.C.

McWilliams, D. A., Berglund, D. R, and Endres G. J. 1999. Soybean growth and management: Quick Guide [Online]. Available at: http://www.bivocational.org/AGRICULTURE/Soybeans/SoybeanGrowthQuickGuide.pdf (verified 26 Nov., 2019).

Miller, P. M. 1976. Effects of some nitrogenous materials and wetting agents on survival in soil of lesion, stylet, and lance nematodes. Phytopathology 66:789-800.

Minton, N. A. 1986. Impact of conservation tillage on nematode population. Journal of Nematology 18:135-140.

Mojtahedi, H., and Lownsbery, B. F. 1976. The effects of ammonia-generating fertilizer on *Criconemoides Xenoplax* in Pot Cultures. Journal of Nematology 8:306-309.

Monfort, W. S., Kirkpatrick, T. L., and Mauromoustakos, A. 2008. Spread of *Rotylenchulus reniformis* in Arkansas cotton field over four-year period. Journal of Nematology 40:161-166.

Moore, W. F. 1984. Soybean cyst nematode. Soybean industry resource committee, Mississippi State University, Starkville, MS.

Natural Resource Conservation Service (NRCS), 2018. Web Soil Survey [Online]. Available at: http//websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx. (Verified 26 Nov., 2019).

Noel, G. R., and Wax, L. M. 2003. Population dynamics of *Heterodera glycines* in conservation tillage and no-tillage soybean/corn cropping systems. Journal of Nematology 35:104-109.

Parker, M. B., Minton, N. A., Brooks, O. L., and Perry, C. E. 1975. Soybean yields and lance nematode population as affected by subsoiling, fertility, and nematicide treatments. Agronomy Journal 67:663-666.

Piper, C. V., and Morse. W. J. 1923. The soybean. New York: McGraw-Hill.

Qiu, L., and Chang, R. 2010. The origin and history of soybean Pp. 169-630 *in* G. Singh, ed. The soybean botany, production and uses. Massachusetts: CABI.

Rich, J. R., Dunn, R. A., and Noling, J. W. 2004. Nematicides: past and present uses. Pp. 1179-1220 *in* Z. Chen., S. Chen, and Dick, eds. Nematology Advances and perspectives. Wallingford, UK: CABI International.

Robbins, R. T., Riggs, R. D., and Von Steen, D. 1987. Results of annual phytoparasitic nematode surveys of Arkansas soybean field, 1978-1986. Annals of Applied Nematology 1:50-55.

Rodríguez-Kábana, R. 1986. Organic and inorganic nitrogen amendments to soil as nematode suppressants. Journal of Nematology 18:129-135.

Roos, J. P. 1964. Effect of soil temperature on development of *Heterodera glycines* in soybean roots. Phytopathology 54:1228-1231.

Schmutz, J., and Cannon, S. 2010. Genome sequence of the paleopolyploid soybean. Nature 463: 178-183.

Schmitt, D. P., Ferris, H., and Barker, K. R. 1987. Response of soybean to *Heterodera glycines* Races 1 and 2 in different soil types. Journal of Nematology 19:240-250.

Simon, A. C. M., Lopez-Nicora H.D., Niblack, T. L., Dayton, A. E., Tomashefski, D., and Paul P. A. 2018. Cropping practices and soil properties associated with plant-parasitic nematodes in corn fields in Ohio. Plant Disease 102:2519-2530.

Slack, D. A., Riggs, R. D., and Hamblen, M. L. 1972. The effect of temperature and moisture on the survival of *Heterodera glycines* in the absence of a host. Journal of Nematology 4:263-266.

Stinner, B. R., and Crossley, D. A. 1982. Nematodes in no-tillage agroecosystems. Pp. 14-28 *in* D. W. Freckman, ed. Nematodes in soil ecosystems. Austin: University of Texas Press, TX.

Thomas, S. H. 1978. Population densities of nematodes under seven tillage regimes. Journal of Nematology 10:24-27.

Todd, T. C., 1996. Effects of management practices on nematode community structure in tallgrass prairie. Applied Soil Ecology 3:235-246.

Tyler, D. D., Overton, J. R., and Chambers, A. Y. 1983. Tillage effects on soil properties, diseases, cyst nematodes, and soybean yields. Journal of Soil and Water Conservation 38:374-376.

Tyler, D. D., Chambers, A. Y., and Young L. D. 1987. No- tillage effects on population dynamics of soybean cyst nematode. Agronomy Journal 79:799-802.

United States Department of Agriculture (USDA), National Resource Conservation Service (NRCS). 2019. Conservation practices that save: crop residue management save energy, save money [Online]. Available at: http://www.nrcs.usda.gov/wps/portal/nrcs/detalfull/national/energy/conservation/?cid=nrcs143_023637 (verified 26 Nov., 2019).

United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS). 2019. USDA reports soybean, corn acreage down [Online]. Available at: http://www.nass.usda.gov/Newsroom/2018/06-29-2018.php (verified 26 Nov., 2019).

United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS). 2019. Principal area planted – States and United States: 2017-2019 [Online]. Available at:https://downloads.usda.library.cornell.edu/usdaesmis/files/j098zb09z/0k225n39n/jw827p632/acrg0619.pdf (verified 12 Oct., 2019).

United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS). 2019. State agriculture overview, Arkansas [Online]. Available at: https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=ARKANSAS (verified 26 Nov., 2019).

Wallace, H. R. 1955. The influence of soil moisture on the emergence of larvae from cysts of the beet eelworm, *Heterodera schachtii.* Annals. Applied Biology 43:477-484.

Wallace, H. R. 1958a. Movement of eelworms. I. The influence of pore size and moisture content of the soil on the migration of larvae of the eelworm, *Heterodera schachtii* Schmidt. Annals. Applied Biology 46:74-85.

Wallace, H. R. 1958b. Movement of eelworms. II. A comparative study of the movement in the soil eelworm, *Heterodera schachtii* Schmidt and of *Ditylenchus dipsaci* (Kuhn) Filipjev. Annals. Applied Biology 46:86-94.

Wrather, J. A., and Koenning, S. R. 2006. Estimate of disease effects on soybean yields in the United States 2003 to 2005. Journal of Nematology 38:173-180.

Young, L. D. 1996. Yield loss in soybean caused by *Heterodera glycines*. Journal of Nematology 28:604-607.

Young, L. D., and Heatherly, L. G. 1988. Soybean cyst nematode effects on soybean growth at controlled water potentials. Crop Science 28:543-545.

Table 1. Soybean harvested in USA in 2019. Adapted from National Statistics Service (2019)

| Rank | State | Area (ha) |
|---|---|---|
| 1 | Illinois | 4,143,981 |
| 2 | Iowa | 3,654,311 |
| 3 | Minnesota | 2,764,003 |
| 4 | North Dakota | 2,367,411 |
| 5 | Indiana | 2,136,740 |
| 6 | Missouri | 2,116,506 |
| 7 | Nebraska | 2,003,194 |
| 8 | Kansas | 1,881,788 |
| 9 | South Dakota | 1,764,429 |
| 10 | Ohio | 1,879,976 |
| 11 | Arkansas | 1,193,822 |

# Chapter 2

## Nematode Population Densities as Affected by Residue and Water Management in a Long-term Wheat-soybean Double-crop in Eastern Arkansas

## Abstract

Soybeans (*Glycine max*) are one of the major row crops in the United States, particularly in Arkansas. The soybean cyst nematode (SCN *Heterodera glycines*) is one of the most damaging pests that can cause major economic losses in soybeans. Little is known concerning the effects of tillage (conventional tillage and no tillage), water management (irrigation and non-irrigation), residue burning (burned and non-burned), and wheat residue level (high and low) on nematodes. Therefore, the objective of this study was to evaluate the effects of the combination of these agronomic practices on natural nematode population densities and change over the growing season in a long-term wheat (*Triticum aestivum*)-soybean rotation on a silt-loam soil in Arkansas. Nematodes were measured in the top 10 cm in July, August, and October 2017 and 2018. Soybean cyst nematode egg concentration was 17.9 times greater ($P < 0.05$) at the end of the growing season in October than earlier in growing season in July and August. The SCN J2 population densities was 3.4 times greater ($P < 0.01$) under the conventional tillage (CT)-burn than under the CT no-burn and no-tillage (NT)-burn treatment combinations. In contrast to under CT, SCN J2 population density was 3.8 times greater under the NT-no-burn than under the NT-burn treatment combinations. The SCN J2 population densities in 2017 was 8.6 times larger ($P$ = 0.03) among the irrigated-CT, irrigated-NT, and dryland-CT than under the dryland-NT combination. However, in 2018, SCN J2 population density was 6.0 times greater in the irrigated-CT than in the dryland-CT treatment combination, but also did not differ from that under irrigated-CT-irrigated-NT, and dryland-CT in 2017.Traditional and alternative wheat-soybean management practices can influence the nematode populations and should be carefully considered to maximize profitability in a soybean crop.

## Introduction

Plant-parasitic nematodes infect and damage a variety of crops (Bridge and Starr, 2007), including soybean (*Glycine max* L.; Koenning et al., 1999). Different nematode species, such as soybean cyst nematode, (SCN, *Heterodera glycines)*, southern root-knot nematode (RKN, *Meloidogyne incognita*), reniform nematodes (*Rotylenchus* spp), lance nematode (*Hoplolaimus* sp.), *Pratylenchus* sp. (lesion nematode), and dagger nematode (*Xiphinema* sp), cause soybean yield losses and are economically important in soybean production in the United States (U.S.; Koenning et al., 1999; Hartman et al., 2015). However, SCN is reported to be the main yield-limiting nematode for soybean production in the U.S. (Wrater and Koenning, 2006; Hartman et al., 2015; Allen et al., 2017). Allen et al. (2017) reported that SCN alone caused an average yield loss of 31%, which was greater than other pests in soybean production in the U.S. and Ontario, Canada in 2011.

Arkansas is the eleventh largest soybean-producing state in the U.S. (USDA NASS, 2019), in which the U.S. is historically the largest soybean-producing country in the world. In Arkansas in 2017, 84.2% of the 1.4 million ha of soybeans planted were irrigated and 15.8% of soybean production was non-irrigated (USDA NASS, 2017). Soybeans are often grown in a double-crop rotation with wheat (*Triticum aestivum*) in the Lower Mississippi River Valley (Brye et al., 2018). The common agronomic management practices for the wheat-soybean, double-crop production system consists of N fertilization of the wheat in the spring to optimize wheat grain production followed by residue burning and conventional tillage after wheat harvest with the subsequent soybean crop grown under furrow irrigation (Brye et al., 2018).

Numerous nematodes species have been identify that negatively affect soybean production in the Lower Mississippi River Valley, which is an important area for soybean production in Arkansas (Heatherly and Young, 1991). In Arkansas, RKN is the main constraint on soybean production, while SCN has been a soybean production problem for many years, and reniform nematode is a relatively new species that has been causing soybean damage in the last 20 to 30 years (Kirkpatrick et al., 2014). Around 30 years ago, SCN was the most prevalent nematode in Arkansas, but more recently, RKN has surpassed SCN infestation in soybean fields (Kirkpatrick and Sullivan, 2016). In Arkansas, of soybean fields surveyed, RKN has been reported to infest 36%, lesion nematode 27%, SCN 15%, reniform nematode 2%, and other nematode species 20% (Kirkpatrick and Sullivan, 2016). Allen et al. (2017) reported that in Arkansas the southern RKN caused an estimated yield loss of 176,629 Mg in 2015 alone. In Arkansas, nematode infestation is expanding at a rate of 0.9 to 1.2 m per year (ASPB, 2019) and, in many cases, without showing visual symptoms of infestation (Young, 1996), while other visual symptoms of nematode infestation are easily confused with nutrient deficiencies (Kirkpatrick et al., 2014).

Management strategies for RKN, SCN, lesion, reniform, and other nematodes species consist of an integrated approach that utilizes resistant cultivars, crop rotation, and the use of nematicides (Kirkpatrick et al., 2014). The use of resistant soybean cultivars is the most economical and effective strategy to manage nematode infestation (Kirkpatrick et al., 2014). However, there is no resistant soybean cultivars for many races of SCN (Bridge and Starr, 2007). Crop rotation can be an effective management practice when selecting the right resistant or non-host soybean cultivar to be used in the cropping sequences. For example, if the SCN is in the field, then corn, rice, peanuts can be grown in rotation because none of these crops are host for SCN. However, if the southern root-knot nematode is the problem, peanuts or cotton should not be planted (Kirkpatrick et al., 2014). Alternatively, nematicides, specifically seed-applied nematicides have been available since 2006, but the use of seed-applied nematicides is best used when nematode population densities are low or when matched with host-plant resistance at greater population densities (Emerson et al., 2018).

However, changing from a monoculture to a crop rotation and/or conversion from traditional to alternative soil and crop management practices can create an ecosystem disturbance that requires some time for the ecosystem, including nematodes and other soil microorganisms, to adjust to a new, stable equilibrium (Brye et al., 2018)

Several studies conducted in the U.S. have investigated on the effects of tillage, crop rotation, and water management on nematode populations in soybean. Baird and Bernard (1984) studied nematode population and community dynamics in soybean-wheat cropping and tillage regimes in Tennessee and concluded that in July SCN J2 population densities were greater under conventional tillage (CT), soybean single-crop system compared to CT wheat-soybean double crop, CT after aerially seeded wheat, soybean no-tillage (NT) after CT wheat, and soybean NT after aerially seeded wheat (Baird and Bernard, 1984). In irrigated soils (i.e., large water contents) in North Carolina, nematode population densities were lower than in non-irrigated soils (i.e., low water contents; Koenning and Barker, 1995). Brye et al. (2018) reported that in eastern Arkansas on a Calloway silt-loam soil (fine-silty, mixed, thermic, Glossaquic Fragiudalfs) the SCN J2 population density was four times greater under the non-burned-irrigated compared to the burned-non-irrigated treatment combination 70 days after planting (Brye et al., 2018). Moreover, the stunt and total nematode populations were almost three times greater under a burn-non-irrigated-NT than under a burn-non-irrigated-CT treatment combination 34 and 70 days after planting, respectively (Brye et al., 2018). However, there is a little information regarding the effects of the combination of tillage, irrigation, residue burning, residue level, and their interactions on plant-parasitic nematodes in a double-crop, wheat-soybean rotation in the U.S., specifically in Arkansas. Therefore, the objective of this study was to evaluate the combined long-term effects of tillage practice [conventional tillage (CT) and no tillage (NT)], water management (irrigation and non-irrigation), residue burning (burned and non-burned), and wheat residue level (high and low) on plant-parasitic nematode population densities and reproduction in the top 10 cm within the growing season and between years in soybean grown in a double-crop production system with wheat on a silt-loam soil in eastern Arkansas. It was hypothesis is that greater nematode (i.e., RKN, SCN, reniform, spiral, lance, stunt, dagger, lesion, ring, and stubby-root) populations exist under CT, irrigated, high-residue-level, and non-burned treatments compared to NT, dryland, low-residue-level, and burned treatments, respectively.

## Materials and Methods

### *Site Description*

Experiments were conducted in spring 2017 at the University of Arkansas, Division of Agriculture Lon Mann Cotton Branch Experiment Station near Marianna, AR, which resides in Major Land Resource Area 134, the Southern Mississippi Valley Loess (N34$^{\circ}$, 44’, 2.26”, W 99 $^{\circ}$, 45’, 51.56”) (Brye et al., 2013). The study area is located on a Calloway silt-loam (fine, mixed, thermic, Glossaquic Fragiudalfs; USDA-NRCS, 2019) soil with 16% sand, 73% silt, and 11% clay in the top 10 cm (Brye et al., 2006) where the top 10 cm encompasses the majority of the A horizon. The study site had been cropped to a wheat-soybean rotation since fall 2001, before which a conventionally tilled soybean monoculture had been the cropping practice for the previous six years (Cordell et al., 2007).

The climate in the region is warm and wet (Brye et al., 2018) and is classified as Humid Subtropical, or Cfa, according to the Koppen-Geiger climate classification system (Arnfield, 2019). The 30-year (i.e., 1981-2010) average monthly air temperature is 16.6$^{o}$C, with the largest average maximum air temperature of 32.9$^{o}$C in July, and the lowest average minimum air temperature of -0.6$^{o}$C in January (NOAA, 2019). The 30-year average annual precipitation is 128.4 cm (NOAA, 2019).

*Treatments and Experimental Design*

Beginning in spring 2002, field treatments, including wheat residue levels (high and low, achieved with differential N fertilization), residue burning and non-burning, and tillage [conventional tillage (CT) and no tillage (NT)], were established and soybeans were grown under furrow-irrigated conditions until 2005 (Brye et al., 2018). The residue level, burning, and tillage treatments were arranged in a split-strip-plot, randomized complete block (RCB) design with three replications for a total of 48, 6-m-long by 3-m-wide field plots, where tillage was stripped across burn treatments and the residue-level treatment was a split within tillage-burn treatment combinations (Brye et al., 2018). In 2005, the study area was split in half, where half of the area remained furrow-irrigated, while the other half was converted to dryland soybean production (i.e., non-irrigated) (Brye et al., 2018). Out of necessity, irrigation treatment blocks were superimposed on the burn treatment blocks, thus the irrigation and burn treatments cannot be simultaneously analyzed in the original RCB design. As a result, for the purposes of this study, following Amuri et al. (2010), a completely random design was assumed for the field treatments, as the addition of the irrigation treatment created 16 residue-level-burn-tillage-water-management treatment combinations that were replicated three times (Amuri et al., 2010).

*Field Management*

Beginning in November 2001, and for every fall thereafter generally between late October and mid-November, wheat was drill-seeded with a 19-cm row spacing at a rate of 168 kg seed $ha^{-1}$ (Norman et al., 2016; Brye et al., 2018). Beginning in March 2002, and for every spring thereafter, wheat was fertilized with a split application of N as urea (46% N), with the first application commonly occurring in early to mid-March and the split application commonly occurring in early to mid-April (Norman et al., 2016; Brye et al., 2018). Between 2002 and 2004, all plots were fertilized with 101 kg N $ha^{-1}$ at the first application time. In the second application time, 101 kg N $ha^{-1}$ were applied to 24 plots to create the high-residue-level treatment (Amuri et al., 2010; Brye et al., 2018). Between Spring 2005 and Spring 2018, a rate of 56 kg N $ha^{-1}$ were applied at both times, for a total N application of 112 kg $ha^{-1}$, to create a high-residue-level treatment in the same 24 plots each year, while no N fertilizer was applied to the other half of the plots to maintain the low-residue-level treatment (Norman et al., 2016; Brye et al., 2018). To demonstrate that different residue levels were attained and substantiate the residue-level treatment, residue levels were measured in all 48 plots after wheat harvest each year, following mowing wheat stubble to a height of approximately 10 cm, by cutting all surface stubble to the soil surface and collecting all surface residue from with a 0.25-$m^2$ metal frame from a representative area within each plot (Brye et al., 2018).

After residue sampling, propane flaming was used to manually burn 24 plots, while the other 24 plots were left unburned. Following imposition of the burn treatment, 24 plots were prepared by CT, which consisted of three passes with a tandem disk to a 5- to 10-cm depth followed by three passes with field cultivator to disperse soil clods and soften the seed bed, whereas the other 24 plots were left without tillage (i.e., NT) prior to soybean planting. From

2002 to 2013, a glyphosate-resistant, maturity group 4 to 5 soybean variety was planted (Brye et al., 2018). In 2017, Go Soy 4912LL, a Liberty-Link, maturity group 4.9, somewhat resistant to the SCN and moderately resistant to the southern RKN soybean cultivar was planted (Go Soy, 2019). In 2018, P 5414 LLS, a Liberty-Link, maturity group 5.4, susceptible to the SCN and moderately resistant to the southern RKN soybean cultivar was planted (Progeny, 2019). In 2017, soybeans were drill-seeded with a 19-cm row spacing on 2 June. In 2018, soybeans were drill-seeded with a 19-cm row spacing on 9 June and replanted on 27 June due to initially low soil moisture and poor stand establishment. The total study area was treated with Liberty-Link herbicide program at least twice after soybean planting in 2017 and 2018 to control weeds, such as pig weed (*Amaranthus palmeri*) and rye grass (*Lolium perernne*). The irrigated half of the study area was watered as-needed approximately three to four times each year for the summer soybean crop only. In general, soybeans were harvested with a plot combine between early October and mid-November each year (Table 1), but specifically on 13 October, 2017 and on 30 October, 2018.

*Soil Sample Collection, Processing, and Analyses*

In May 2017 and 2018, prior to soybean planting, one soil sample per plot was manually collected using a 4.8-cm-diameter stainless steel core chamber and a slide hammer from the top 10 cm. In addition to encompassing most of the organic matter concentration and A horizon, the top 10 cm is also the typical zone of greater microorganism activity. Soil samples were oven-dried at 70ºC for 48 hours and weighed for bulk density determination, then crushed and sieved through a 2-mm mesh screen for chemical analyses. Soil pH and electrical conductivity (EC) were determined potentiometrically on a 1:2 soil mass to distilled water volume paste.

Subsamples were extracted with Mehlich-3 extraction solution in a 1:10 soil mass: extractant volume ratio (Tucker, 1992) and analyzed for extractable soil nutrients concentrations (i.e., P, K, Ca, Mg, S, Na, Fe, Mn, Zn, and Cu) by inductively coupled, argon-plasma spectrometry (CIROS CCD model, Spectro Analytical Instruments, MA). Total carbon (TC) and nitrogen (TN) concentrations were determined by high temperature combustion (Vario MAX Total C and N Analyzer, Elementar Americas Inc., Mt. Laurel, NJ). Using measured TC and TN concentrations, the soil C:N ratio was calculated. Soil organic matter (SOM) concentrations was determined by weight-loss-on-ignition after 2 hours at 360°C. Soil contents (kg $ha^{-1}$) were calculated from measured concentrations (g $kg^{-1}$) and measured bulk densities in the top 10 cm of each plot.

In both years, soil samples were collected from the top 10 cm approximately 1 and 2 months after soybean planting and near soybean harvest (i.e., on 7 July, 15 August, and 12 October 2017 and on 9 July, 10 August, and 15 October 2018). Ten soil samples were manually collected with a 2-cm diameter push probe from within the planted soybean row in a criss-cross pattern within each plot and combined for one sample per plot (Brye et al., 2018). Soil samples were kept in the dark and at room temperature until being sent within three days to the Arkansas Nematode Diagnostic Laboratory located in Hope, AR for nematode population density analysis (Brye et al, 2018). The abundance of 10 different genera of plant-parasitic nematodes (i.e., soybean cyst nematode second-stage juveniles [J2], dagger, reniform [*Rotylenchulus* spp.] lance [*Hoplolaimus* spp.], lesion, spiral, ring [*Criconemella* spp.], stubby-root, stunt, and root-knot nematode), and SCN eggs were determined for each soil sample.

Similar to procedures described by Monfort et al. (2008) and Brye et al. (2018), nematodes were extracted from a 100 $cm^3$ of fresh soil using a semi-automatic elutriator (Byrd et al., 1976) and SCN cyst collected on 60-mesh sieves followed by centrifugal flotation (Jenkins, 1964). Nematode identification and counting were conducted under 40 to 60x magnification with a stereoscope. Cysts of SCN that were trapped on the 60-mesh sieves of the elutriator were collected and crushed in a glass-tissue homogenizer to free eggs that were subsequently counted at 40x magnification (Barker, 1985). Of the 10 nematode genera that were quantified, the total number of plant-parasitic nematodes and the number of plant-parasitic nematode genera present per plot were also calculated for statistical analyses.

*Statistical Analyses*

An analysis of variance (ANOVA) was performed separately using PROC GLIMMIX in SAS (version 9.4, SAS Institute, Inc., Cary, NC) to determine the effects of tillage (CT and NT), irrigation (irrigated and non-irrigated), burning (burn and no burn), residue level (high and low), and their interactions on early season soil chemical and physical properties in the top 10 cm before soybean planting. Means were separated by least significant difference (LSD) and a significance level (α) of 0.05 level. A separate ANOVA was conducted using PROC GLIMMIX in SAS to evaluate the effects of residue level, burning, tillage, irrigation, date (July, August, October) year (2017 and 2018), and their interactions on plant-parasitic nematode population densities in the top 10 cm. If a plot had none of a particular nematode species, then the analyzed dataset retained a zero for that plot-species combination. Means were separated by least significant difference (LSD) and a significance level (α) of 0.05 level. Linear correlations using Minitab (Version 16. Inc., State College, PA) were performed between soybean grain yield and each nematode species. A separate linear correlation was conducted between soil properties and nematode population densities were conducted in Minitab. Means were separated by LSD and a significance level (α) of 0.05 level.

## Results and Discussion

### Initial Soil Properties

Soil physical and chemical properties contribute to soil fertility and plant growth, hence also contribute to soil microorganism growth and behavior. Therefore, it was necessary to establish how various soil physical and chemical properties differed among field treatment combinations prior to the two consecutive growing seasons of nematode assessment. As was expected, after 16 complete cropping cycles in the wheat-soybean, double-crop rotation, nearly all measured soil properties in the top 10 cm were affected by the imposed residue and water management practices (Table 2). Soil pH, bulk density (BD), and extractable soil K, S, and Na contents differed ($P < 0.05$) among irrigation treatments (Table 2). Averaged across tillage, burning, and residue level, soil pH and extractable soil S and Na contents were greater under long-term irrigated (6.7 and 24.5 and 33.1 kg $ha^{-1}$, respectively) than under long-term dryland conditions (6.1 and 19.8 and 22.8 kg $ha^{-1}$, respectively). However, soil BD and extractable soil K content were greater under dryland (1.3 g $cm^{-3}$ and 109 kg $ha^{-1}$, respectively) than under irrigated conditions (1.2 g $cm^{-3}$ and 73.0 kg $ha^{-1}$, respectively).

Soil pH and extractable soil Mg, Na, Fe, and Mn contents in the top 10 cm also differed ($P < 0.05$) among tillage treatments (Table 2). Averaged across irrigation, burning, and extractable soil Mg, Na, and Mn contents were greater under long-term CT (6.5 and 405, 29.4, and 255 kg $ha^{-1}$, respectively) than under long-term NT (6.2 and 347, 25.6, and 234 kg $ha^{-1}$, respectively). Soil pH and extractable soil Na, Mn, and Zn contents in the top 10 cm also differed ($P < 0.05$) among burn treatments (Table 2). Averaged across irrigation, tillage, and residue level, soil pH and extractable soil Mn and Zn contents were greater under long-term no-burn (6.5 and 266 and 3.4 kg $ha^{-1}$, respectively) than under long-term burning (6.2 and 225 and 2.6 kg $ha^{-1}$, respectively), while extractable soil Na content was greater under the burn (29.9 kg $ha^{-1}$) than under the no-burn (25.2 kg $ha^{-1}$) treatment. Averaged across irrigation, tillage, and burning, extractable soil P content was greater (*P* = 0.01; Table 2) under the long-term low-residue (40.9 kg $ha^{-1}$) than under the long-term high-residue level (36.1 kg $ha^{-1}$) treatment. Norman et al. (2016) reported that in the same plots of this study between 2001 and 2014, extractable soil P contents increased under dryland systems until 9 years after the beginning of the new management, but extractable soil P decreased under irrigated conditions. Greater aboveground residue production clearly removed more P from the soil.

Though the total C and N concentrations in the top 10 cm were unaffected by any field treatments (Table 2) after 15 complete cropping cycles and averaged 0.11% and 1.21%, respectively, across the entire study area, the soil C:N ratio in the top 10 cm differed among irrigation-tillage (*P* = 0.01) and tillage-burning-residue level (*P* = 0.02) treatment combinations (Table 2). Averaged across burning and residue level, the soil C: N ratio was greater under the irrigated-CT (11.5) than in the other three treatment combinations, which did not differ and averaged 10.9 (Figure 1). In addition, averaged across irrigation, the soil C: N ratio was greater under CT-burn-high-residue-level (11.3) than under the NT-no-burn-low-residue-level (10.7), while all six other treatment combinations were intermediate and not differ (Figure 1).

Soil EC and extractable soil Mg and P contents in the top 10 cm differed ($P < 0.05$) among irrigation-burn treatment combinations (Table 2). Averaged across tillage and residue level, soil EC (Figure 1) and extractable soil Mg content (Figure 2) were greater under the irrigated-burn (0.3 dS $m^{-1}$ and 439 kg Mg $ha^{-1}$, respectively) than in the dryland-burn and -no burn treatment combinations, which did not differ and averaged 0.2 dS $m^{-1}$ and 352 kg Mg $ha^{-1}$, respectively, while soil EC in the irrigated-no-burn treatment combination (0.2 dS $m^{-1}$) was lower than that in the irrigated-burn, but greater than that in the dryland treatments (Figure 1). In contrast, extractable soil P content was greater in the dryland-no-burn (44.9 kg $ha^{-1}$) than that in the other three irrigation-burn treatment combinations, which did not differ and averaged 36.6 kg $ha^{-1}$ (Figure 2).

Extractable soil Fe content in the top 10 cm differed ($P$ = 0.03) among irrigation-tillage-burn treatment combinations (Table 2). Averaged across residue level, extractable soil Fe content was greater under the dryland-CT-no burn (403 kg $ha^{-1}$) than under all irrigation-tillage-burn treatment combinations (Figure 2). Extractable soil Fe content under the other three dryland treatment combinations did not differ (Figure 2). Extractable soil Fe content was also greater in the irrigated-CT-burn (328 kg $ha^{-1}$) than in the other three irrigated treatment combinations (Figure 2).

Extractable soil Ca, Cu, and B contents and SOM concentration in the top 10 cm differed among irrigation-tillage-burning-residue-level treatment combination ($P$ < 0.05; Table 3). Extractable soil Ca content was greater in the dryland-CT-no-burn-high- and low-residue-level (1938 and 1942 kg $ha^{-1}$, respectively) than in the irrigated-NT-no-burn-high-residue-level (1257 kg $ha^{-1}$) treatment combination, while extractable soil Ca content under the other irrigation-tillage-burning-residue level treatment combinations were intermediate (Table 3).

Extractable soil Cu content was greater under the dryland-NT-burn-high-residue-level (2.1 kg $ha^{-1}$) compared to the irrigated-CT-no burn-high- residue-level and irrigated-NT-burn-high-residue-level treatment combinations, which did not differ and averaged 1.2 kg $ha^{-1}$, while extractable soil Cu contents for all other irrigation-tillage-burning-residue-level treatment combinations were intermediate (Table 3). Extractable soil B content was greater in the irrigated-CT-no-burn-high-residue-level (1.4 kg $ha^{-1}$) than in the dryland-CT-burn-low- and the dryland-

NT-burn-high- and -low-residue-level treatment combinations, which did not differ and averaged 0.6 kg $ha^{-1}$ (Table 3). Soil organic matter concentration results were variable and inconsistent, but SOM concentration was numerically largest under long-term dryland-NT-no-burn management, which did not differ between residue-level treatments, and numerically lowest under the dryland-NT-burn-high- and irrigated-NT-burn-low-residue-level treatment combinations, which also did not differ (Table 3). Residue level did not affect soil pH, EC, BD, extractable soil K, Mg, S, Na, Fe, Mn, and Zn contents, or TC and TN concentrations (Table 3).

**Growing-season Nematode Population Densities**

Various nematode species and total nematode population densities in the soil were affected by one or several treatments within and/or across two growing seasons after 15 (2017) and 16 years (2015) of complete cropping cycles under a wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas (Table 4). Treatment effects on individual nematode properties and nematode species will be presented. However, some nematode species had small populations in the soil and could not be formally statistically analyzed. One possible explanation for small nematode population densities in the soil could be that nematodes were distributed deeper than 10 cm in soil profile. Another reason that nematodes, such as the RKN and reniform nematode, may have not been present in the soil may have been due to the long-term effects at the study area that might have modified the soil environment for RKN survival and reproduction. The RKN, stubby root, and ring nematodes were present in less than 13% of the field plots across both years and no dagger or reniform nematodes were present in the top 10 cm during the three in-season sample dates in 2017 and 2018.

*Soybean Cyst Nematode*

*Eggs*

As a historically significant soybean pest throughout the U.S. and particularly in Arkansas, SCN was present in 16% and 18% of the plots as eggs and stage 2 juveniles (J2), but neither were present at a concentration that was expected to negatively affect soybean growth or yield. The maximum concentration of SCN J2s were 153 nematodes (100 $cm^3$)$^{-1}$ soil under the CT-burn-low residue-level-dryland treatment combination in 2017, which did not exceed the threshold level [500 nematodes (100 $cm^3$)$^{-1}$] for expected negative effects on soybean production in Arkansas (Kirkpatrick et al., 2014). However, 77 and 83% of the 48 field plots had no detectable SCN J2 concentration at any time during the soybean growing season in 2017 and 2018, respectively. Soybean cyst nematode egg population densities in the top 10 cm of soil differed among the three in-season sampling dates ($P < 0.05$ Table 4) and, averaged across sampling dates and years, differed among irrigation-tillage-burn treatment combinations ($P = 0.01$; Table 4). Averaged over all four field treatments and years, SCN egg concentration was 17.9 times greater at harvest than at planting and mid-season, which did not differ. This result was not surprising given that the life cycle of the nematodes begins as the host plant starts to grow because nematodes use plants as source of food, which permit the nematode to grow, develop, and reproduce, thus increasing their population from the beginning to the end of the soybean growing season. In contrast to the results of this study, Brye et al. (2018) reported that SCN egg population densities in the top 10 cm of a Calloway silt-loam did not increase overtime during the soybean growing season under the no burn-irrigated compared to the burn-irrigated treatment combination.

Averaged over sample time within a growing season and year, SCN egg population densities in the soil was numerically largest [2.9 nematodes (100 $cm^3$)$^{-1}$] in the CT-no-burn combination under irrigated conditions and lowest [0.1 nematodes (100 $cm^3$)$^{-1}$] in the CT-no-burn combination under dryland soybean production (Figure 3). Soybean cyst nematode egg population density was at least 10.7 times greater in the CT-no-burn-irrigated than in the NT-no-burn-irrigated and CT-no-burn, NT-burn, and NT-no-burn treatment combinations under dryland production, which did not differ (Figure 3). However, SCN egg concentration in the CT-no-burn-irrigated was also similar to that in the CT- and NT-burn-irrigated and CT-burn-dryland treatment combinations (Figure 3). Under dryland production, SCN egg population density was unaffected by tillage or burn field treatments (Figure 3). Furthermore, under the dryland soybean production, SCN egg population density was unaffected by tillage or burn treatments (Figure 3). The greater concentration of SCN eggs under CT in irrigated conditions may have resulted from nematode spread along the field as a result of tillage operations, as the tillage treatment was imposed as a continuous strip across the study area, which was facilitated by periodic water flow from furrow irrigation. These results are consistent with a soybean study conducted in Tennessee on a Lexington silt loam (fine-silty, mixed, active, thermic Ultic Hapludalfs) where it was reported that the SCN population density was lower under NT compared to other tilled systems, such as disked, chiseled, sub-soiled under rows, and sub-soiled between rows (Tyler et al., 1983). Moreover, Hershman and Bachi (1995) reported that, in a wheat-soybean, double-crop study conducted from 1990 to 1992 in Kentucky on a Crider silt loam (fine-silty, mixed, active, mesic Typic Paleudalfs) and on a Pembroke silt loam soil (fine-silty, mixed, active, mesic Mollic Paleudalfs), SCN egg population density was numerically larger under minimum-tillage than no-tillage at soybean planting, but the results were the opposite at harvest in 1992. Bao et al. (2011)

also reported that in the same area of this study, SCN eggs population densities was greater under the continued CT soils compared to the NT soils because soil disturbance decreased fungi species that parasite SCN J2s.

One possible reason for greater SCN eggs under irrigation may have been due to greater soil moisture content under irrigated than dryland production (Table 15), which may have provided a more conducive environment for SCN survival, migration, feeding, development, and reproduction. In contrast to the results of this study, Koenning and Barker (1995) reported greater SCN egg and J2 population densities under dryland than irrigated soybean production in six different soils (Cecil sandy clay, Cecil sandy clay loam, Fuquay sand, Muck, Norfolk sandy loam, and Portsmouth loamy sand) in North Carolina.

*Juveniles*

Soybean cyst nematode J2 population densities differed among tillage-burn ($P < 0.01$; Table 4) and year-irrigation-tillage ($P = 0.03$; Table 4) treatment combinations. Averaged across residue levels, irrigation, sample dates within the growing season, and years, SCN J2 population density [1.1 nematodes $(100\ cm^3)^{-1}$] was 3.4 times greater under the CT-burn than under the CT no-burn and NT-burn treatment combinations, which did not differ and averaged 0.49 nematodes $(100\ cm^3)^{-1}$ (Figure 4). In contrast to under CT, SCN J2 population density was 3.8 times greater under the NT-no-burn than under the NT-burn treatment combinations (Figure 4).

Residue burning effects on nematodes have been rarely been studied in the field, which makes this field study unique. Burning in combination with CT affects the amount of crop residue left on the soil surface, leading also to changes in soil organic matter and soil moisture content. One plausible explanation for greater SCN J2 population densities under the CT-burn than under the CT-no burn combination may be due to the numerically lower SOM concentration in the CT-burn combination (Table 5), which could have resulted in less organic substrate for biological control agents or soil-suppressant organisms that prey on parasite nematodes. In addition, Norman et al. (2016) reported that in the same plots of this study, SOM content decreased at a rate of -0.02 kg $m^{-2}$ $yr^{-1}$ under burned treatment and increased at a rate of 0.02 kg $m^{-2}$ $yr^{-1}$ under no- burn treatment. However, the greater SCN J2 population density under the NT-no burn than under the NT-burn treatment combination could be because of greater soil moisture content (Table 15).

Averaged across residue levels, burn, and sample date within the growing season, SCN J2 population in 2017 was 8.6 times larger among the irrigated-CT, irrigated-NT, and dryland-CT combinations, which did not differ and averaged 1.8 nematodes (100 $cm^3)^{-1}$, than under the dryland-NT combination (Figure 5). However, in 2018, SCN J2 population density was 6.0 times larger in the irrigated-CT than in the dryland-CT treatment combination, but also did not differ from that under irrigated-CT, irrigated-NT, and dryland-CT in 2017 (Figure 5). Furthermore, SCN J2 was unaffected by tillage under irrigated conditions in 2017 and 2018 and under dryland production in 2017 (Figure 5). Treatment effects on SCN J2 population densities differed between years, where SCN J2 population density was generally greater in 2017 than in 2018. The greater SCN J2 population densities in 2017 may be explained because the 2017 growing season was cooler (soil temperature 26.5$^{o}$C at 50 cm deep) with more rainfall (89.5 cm) compared to the 2018 growing season, which was slightly warmer (soil temperature 27.4$^{o}$C at 50 cm deep) and somewhat dryer (61.67 cm), respectively (Table 13). The SCN J2 population densities may have been more affected by soil moisture than soil temperature due to the soil temperature variation, 15 to 32°C (Moore, 1984), being within the optimal range for nematode development.

Various studies on the influence of cropping practices on nematodes soil abundance (Brye et al., 2018; Bao et al., 2011; Heatherly et al., 1992; Baird and Bernard, 1984) have reported variability in the presence and population density of SCN J2 among different cropping practices. Results of this field study also showed that different irrigation, tillage, residue level, and residue burning combinations resulted in different SCN J2 population densities, indicating the potentially complex response nematodes have to agricultural management.

*Lance Nematode*

Lance nematode was present in 22% of the samples analyzed in 2017 and 2018. Lance nematode population densities differed among irrigation-tillage treatment combinations ($P =$ 0.03; Table 4). Averaged over burn, residue level, sample date within the growing season, and year, lance nematode population density was 5.0 and 17.4 times greater under dryland production [1.7 nematodes (100 $cm^3)^{-1}$], which was unaffected by tillage treatment, than under the irrigated-CT and irrigated-NT treatment combinations, respectively (Figure 6). Lance nematode population density under the irrigated-CT was also 3.5 times greater than that under the irrigated-NT treatment combination (Figure 6).

Hartman et al. (2015) and Koenning et al. (1999) reported that the lance nematode can causes soybean yield losses in the U.S. In addition, Robbins et al. (1987) reported that lance nematode has infested soybean fields in Arkansas in the past. After 16 and 17 years of continuous and consistent management, results showed that lance nematode population densities in the top 10 cm were favored by dryland production conditions, which differed from the original hypothesis that nematode abundance, in general, would be greater under irrigated conditions. In the same plots as used in this study, Brye et al. (2018) reported that lance nematode was greater under the burn-non-irrigated-NT than under the burn-non-irrigated-CT treatment combination after 15 years of consistent management.

### *Lesion Nematode*

Lesion nematode was present in 11% of the soil samples analyzed in 2017 and 2018. Lesion nematode population densities differed between tillage treatments (*P* = 0.02; Table 4) and among irrigation-burn treatment combinations (*P* = 0.02; Table 4). Averaged across burn, residue level, irrigation, sample date within growing seasons, and year, lesion nematode population density was 2.5 times greater under NT [0.3 nematodes $(100\ cm^3)^{-1}$] than under CT [0.12 nematodes $(100\ cm^3)^{-1}$]. Kirkpatrick et al. (2014) reported that lesion nematode causes soybean yield loses in the Arkansas, However, Hartman et al. (2015) reported that lesion nematode has not been well-studied yet in the U.S. Lesion is an endoparasitic nematode, thus total concentration of lesion could have been greater, but we did not measure nematode on plant tissues.  One possible explanation may be due to the NT might have caused greater vertical distribution in the soil rather than horizontal distribution as caused by CT management. In contrast to this study, in Indiana on a silt-loam soil, densities of lesion nematode in a soybean crop were greater under CT than in under zero-tillage, which was attributed to the larger and more robust soybean roots under CT (Alby et al., 1983). However, in the same soil, the population of lesion nematode was more uniformly spatially distributed in non-tilled than in tilled soybean plots (Alby et al., 1983). Averaged across tillage, residue level, sample date within growing seasons, and year, lesion nematode population density was 5.6 times greater under the dryland-burn than under the dryland-no-burn treatment combination but was unaffected by burning under irrigated conditions (Figure 7). The dryland-burning treatment combined might have played a role in decreasing SOM (Table 2) and soil-suppressive microorganisms in the soil, resulting in less efficient biological control and increasing the population of the lesion nematode. Lesion nematode population density under irrigated conditions was also similar to both burning and non-burning under dryland production (Figure 7). Kirkpatrick (2017) reported that the lesion nematode tested positive in 20% of soybean fields grow in Arkansas in 2015. For this reason, management practices should be considered to keep the lesion nematode below the threshold damage-causing level and to avoid spreading the lesion nematode into more farmland area.

*Spiral Nematode*

Spiral nematode was present in 38% of the soil samples analyzed in 2017 and 2018. **S**piral nematode population densities differed among year-irrigation-tillage ($P < 0.01$; Table 4), year-irrigation-residue level ($P < 0.05$; Table 4), and irrigation-tillage-burn-residue level ($P = 0.02$; Table 4). Similar to the effect on SCN J2, averaged across burn, residue level, and sample date within the growing season, spiral nematode was 52.6 times greater under irrigated-CT [31.84 nematodes $(100\ cm^3)^{-1}$] than under the irrigated-NT, dryland-CT, and dryland-NT treatment combinations in 2017, all of which averaged had less than 0.6 nematodes $(100\ cm^3)^{-1}$ (Figure 8). However, spiral nematode population density was similar among the irrigated-CT, irrigated-NT, and dryland-CT treatment combinations in 2018, which also was similar to that in the irrigated-CT treatment combination in 2017, and was at least 8.1 times greater than under the dryland-NT treatment combination in 2018 (Figure 8). Allen et al. (2017) reported that spiral nematode caused soybean yield losses in the southern U.S. from 2010 to 2014. Likewise, irrigation in combination with CT treatment may have caused greater spiral nematode population densities in the soil during the soybean growing season, while irrigated-NT and dryland-tillage treatment combinations did not provide a favorable soil environment for nematode survival and reproduction in 2017. In contrast, spiral nematode appears to have been affected by the same environmental conditions (Table 13) as the SCN J2 in 2018.

Averaged across tillage, burn, and sample date within the growing season, spiral nematode population density was unaffected by residue level under irrigated conditions in 2017 and was at least 20.7 times greater than under the high- and low-residue-level-dryland treatment combinations, in which that under the high-residue level was 7.2 times greater than under the low-residue level (Figure 9). Similar to 2017, spiral nematode population density was unaffected by residue level under irrigated conditions in 2018 and was similar to that under irrigated conditions in 2017. Spiral nematode population density in 2018 under the dryland-high-residue-level was also similar to that under irrigated conditions in 2017 and 2018. Spiral nematode population density was also 5.7 times greater under the irrigated-high- than under the dryland-low-residue-level treatment combination in 2018 (Figure 9). The dryland-low-residue-level treatment combination in 2017 had the lowest spiral nematode population densities among all other irrigation-residue-level treatment combinations (Figure 9). Similar to the previous nematode species, the irrigation (irrigated and dryland) treatment appeared to have a major influence on nematode population densities in the soil. The lowest spiral nematode population densities in the soil under dryland-low residue level in 2017 may have been due to lower soil moisture contents in the dryland compared to the irrigated soybean production (Table 15) which may have hindered spiral nematode development. To the best of our knowledge, no previous studies have attempted to determine the effects of agricultural practices on spiral nematode population densities.

Averaged across sample date within the growing season and year, spiral nematode population density was numerically largest [24.6 nematodes (100 $cm^3$)$^{-1}$] under the irrigation-CT-no-burn-low-residue-level and smallest under the dryland-NT-no-burn-low-residue-level [0.11 nematodes (100 $cm^3$)$^{-1}$] treatment combinations (Table 5). Under irrigated conditions, spiral nematode population density was lowest under the irrigated-NT-no-burn-high-residue-level [0.8 nematodes (100 $cm^3$)$^{-1}$] than under all seven other irrigation-tillage-burn-residue-level treatment combinations, which did not differ and were also similar to that under the dryland-CT-burn-high-residue-level treatment combination (Table 5). However, under dryland conditions, spiral nematode population density did not exceed 1.5 nematodes (100 $cm^3$)$^{-1}$ in all seven tillage-burn-residue-level treatment combinations, except for in the dryland-CT-burn-high-residue-level treatment combination (Table 5). The numerically larger spiral nematode population densities in the soil occurred under the irrigated-CT-no burn-high and –low-residue level compared to the dryland-NT-no burn- low-residue-level. Results suggested once again that irrigation favors nematode development in the soil and dryland does not. In addition, results support that CT favors nematode spread compared to NT and the no-burn-low-residue treatment combination did not have a consistent effect on spiral nematode. In contrast to the effects of burning in this study, a study in a prairie on an Irwin silty-clay-loam soil (fine, mixed, superactive, mesic Pachic Argiustolls) with big bluestem (*Andropogon gerardii),* Indian grass (*Sorghastrum nutans*), and switchgrass (*Panum virgatum*) as the prevalent vegetation, in which annual burning and non-burning treatments were applied, reported that spiral nematode populations at the 20-cm soil depth were 137% greater under the annually burned compared to the unburned treatment after nine years of management (Todd, 1996).

*Stunt Nematode*

Stunt nematode was present in 68% of soil samples analyzed in 2017 and 2018. Compared to the other individual nematode species, stunt nematode population density was affected by numerous complex treatment interactions. Stunt nematode population densities differed among year-irrigation-tillage-burn ($P = 0.02$), year-irrigation-tillage-residue level ($P = 0.01$), year-irrigation-burn-residue level ($P < 0.01$), and irrigation-tillage-burn-residue level ($P < 0.01$) treatment combinations (Table 4). Averaged across residue level and sample date within the growing season, stunt nematode population density was numerically greatest in the irrigated-NT-burn treatment combination in 2017 and smallest in the irrigated-NT-no-burn treatment combination in 2018 (Table 6). Stunt nematode population density was at least seven times larger in 2017 under the irrigated- and dryland-NT-burn treatment combinations, which did not differ, than all irrigation-tillage-burn treatment combinations in 2018 and the irrigated- and dryland-CT-no-burn treatment combinations in 2017 (Table 6). With the exception of the tillage-burn combinations under irrigated conditions in 2018, stunt nematode population density was numerically greater under burning than non-burning in all other irrigation-tillage-burn treatment combinations in 2017 and 2018 (Table 6).

Handoo et al. (2014) reported that stunt nematode is known to cause damage to several crops. The largest stunt nematode population densities under the irrigated-NT-burn treatment combination in 2017 may have been influenced by greater soil moisture (Table 13), vertical nematode distribution in the soil as a result of no soil disturbance (NT), and lower concentrations of soil suppressants because of the lower organic matter as a result of burning (Table 15). However, the lowest stunt nematode population density may have been because, under the irrigated-NT-no burn treatment combination, soil-suppressant microorganisms had effective control over the stunt nematode.

Averaged across burn and sample date within the growing season, stunt nematode population density was numerically greatest in the dryland-NT-high-residue-level treatment combination in 2017 and smallest in the irrigated-NT-low-residue-level treatment combination in 2018 (Table 7). Results were generally variable and inconsistent. Residue level did not affect stunt nematode population densities within the irrigated-CT and dryland-NT combinations in 2017 or within irrigated- and dryland-CT combinations in 2018. In contrast, stunt nematode population density was greater in the high- than in the low-residue level within the dryland-CT combination in 2017 and within the irrigated-NT combinations in 2018, while stunt nematode population density was greater in the low- than in the high-residue level in the irrigated-NT combination in 2017 and the dryland-NT combination in 2018 (Table 7). One plausible explanation for the greatest nematode population density under the dryland-NT-high-residue-level treatment combination in 2017 and smallest population densities in the irrigated-NT-low-residue-level treatment combination in 2018 may have been because of more favorable weather conditions in 2017 during the soybean growing season (Table 14). In contrast to the hypothesis, dryland favored stunt nematode population densities in combination with NT-high residue level, which may be explained by the vertical distribution of the nematode in the soil caused by the NT.

Averaged across tillage and sample date within the growing season, stunt nematode population density was numerically greatest in the dryland-burn-high-residue-level treatment combination in 2017 and smallest in the irrigated-no-burn-high-residue-level treatment combination in 2017 (Table 8). Results were also generally variable and inconsistent. Similar to previously, residue level did not affect stunt nematode population densities in six of the eight year-irrigation-burn combinations, while stunt nematode population density was greater in the low- than in the high-residue level in the irrigated-no-burn combination in 2017 and in the dryland-no-burn combination in 2018 (Table 8). Results suggest that the effect of burning favored stunt nematode population densities in 2017, indicating that the burn treatment may have decreased the population densities of biological control organisms that preyed on or parasitized stunt nematodes. In addition, the warmer and moist weather conditions in 2017 compared to the weather in 2018 may have favored stunt nematode population densities (Table 14).

Similar to the effect on spiral nematode, averaged across sample date within the growing season and year, stunt nematode population densities also differed among field treatment combinations only, without differences over time. Stunt nematode population density was numerically greatest in the dryland-NT-burn-high-residue-level treatment combination and smallest in the irrigated-NT-no-burn-low-residue-level treatment combination (Table 9). Results were also generally variable and inconsistent. Stunt nematode population density was unaffected by residue level in five of the eight irrigation-tillage-burn treatment combinations, while stunt nematode population density was greater under the low- than the high-residue level in the irrigated-CT-no-burn and dryland-NT-no-burn treatment combinations, but was greater under the high- than under the low-residue level in the dryland-CT-no-burn treatment combination (Table 9). Stunt nematode population density was numerically larger in 2017 compared to the 2018, which suggested that stunt nematode population was favored by cooler temperatures and more rainfall rather than the warmer and dryer weather conditions as was reported for the SCN J2 and spiral nematode (Table 14). One previous study conducted in the same plots as used for the current research reported that stunt nematode populations were almost three times greater under the burn-non-irrigated-NT than under the burn-non-irrigated-CT treatment combination 34 and 70 days after planting, respectively (Brye et al., 2018). Since field treatment effects on stunt nematode population densities were inconsistent, thus further research is needed to determine the effects of irrigation-tillage-burning treatment combinations on various nematode species, include stunt nematode.

*Total Nematode Concentration*

Summing across all individual nematodes evaluated, total nematode population densities differed among year-irrigation ($P$ = 0.03), irrigation-tillage-burn ($P$ = 0.02), and year-tillage-burn-date ($P$ = 0.04) treatment combinations (Table 4). Averaged across tillage, burn, residue level, and sample date within the growing season, within each year separately, total nematode population densities were unaffected by irrigation treatment, but was 2.3 times greater under dryland production in 2017 than under dryland production in 2018, while that under irrigated conditions was intermediate and did not differ across both years, averaging 119.5 nematodes $(100\ cm^3)^{-1}$ (Figure 10). A possible explanation for the greater total nematode population densities under dryland in 2017 than under the same treatment in 2018 may have been related to weather differences, where the 2017 growing season was cooler and more rainfall than that in 2018, which was slightly warmer and drier (Table 14).

Similar to the effect on SCN eggs, averaged across residue level, sample date within the growing season, and year, total nematode population densities numerically greatest in the irrigated-NT-burn and smallest in the irrigated-NT-no-burn treatment combination (Figure 9). Total nematode population densities were 1.9 times greater under the CT-burn, CT-no burn, and

NT-burn, which did not differ and averaged 141.5 nematodes (100 $cm^3$)$^{-1}$ than under the NT-no burn treatment combination under irrigated conditions, while that under the NT-burn was 1.6 times greater than under the CT-no burn treatment combination under dryland soybean production (Figure 9). In addition, total nematode population densities were unaffected by residue burning under both irrigation treatments under CT and under dryland production under NT (Figure 9). The greater total nematode abundance under irrigated-NT-burn compared to the irrigated-NT-no-burn treatment combination supports the idea that the burn treatment has a negative effect on soil-suppressive microorganisms. A study in France, a 14-year-long study on a silt-loam-textured Luvisol in which winter wheat was planted each year concluded that the total nematode population increased by a factor of seven under long-term NT systems (Henneron et al., 2015).

Averaged across irrigation and residue level, total nematode population densities were numerically greatest in the NT-burn combination early in the growing in July in 2017 and smallest in the NT-burn combination early in the growing season in July in 2018 (Table 10). Total nematode population densities were greater in July and August in the NT-burn combination in 2017, which did not differ and averaged 408.1 nematodes (100 $cm^3$)$^{-1}$, than in all other year-tillage-burn-sample date combinations (Table 10). Total nematode population densities in the soil decreased from July to October under CT in both residue burning treatments and under NT in the burn treatment in 2017 (Table 10). However, similar to SCN eggs, total nematode population densities increased from July to October under the same treatment combinations in 2018 (Table 10). Similar to previous nematode species, the greater total nematode population densities in 2017 may be explained by the different weather conditions between 2017 and 2018 (Table 14). The total nematode increment from the beginning to the end of the growing season in 2018 was likely due to food availability. However, the decreased total nematode population densities from July to October in 2017 was likely due to less favorable soil environmental conditions (i.e., soil moisture and temperature) for reproduction and survival.

**Correlations Among Nematodes and Soybean Yield**

After 16 (2017) and 17 years (2018) of complete cropping cycles in a wheat-soybean, double-crop production system under several agronomic practices of water management and residue level, soybean grain yield ranged from a minimum of 1609 kg $ha^{-1}$ in irrigated-NT-burn-high residue level treatment combination to a maximum of 3397 kg $ha^{-1}$ in dryland-CT-burn-high residue level what treatment combination in 2017. In 2018, soybean grain yield ranged from a minimum of 1565 kg $ha^{-1}$ in dryland-NT-no burn-high residue level treatment combination to a maximum of 3293 kg $ha^{-1}$ in irrigated-CT-burn-low residue level treatment combination. Averaged across all field treatments, the mean soybean yield was 2765 and 2581 kg $ha^{-1}$ in 2017 and 2018, respectively. These results are consistent with the long-term study conducted in the same plots and under the same management as the current study, which showed that soybean yield started to decrease 9 years after crop management conversion under irrigated soybean production, but soybean yields slightly increased under dryland production by 11 years after management practice conversion (Norman et al., 2016). In addition, a recent study conducted in the same plots as the current study reported that soybean yield was numerically greater under burn-dryland-high-residue-level compared to the burn-dryland-low-residue-level treatment combination (Brye et al., 2018).

Since crop yield variability is known to be affected by soil physical and chemical properties, plant pests, and diseases, it was expected that soybean yield variations were related to at least some nematode properties. However, combined across years, nematode species (i.e., SCN eggs and J2, lance, lesion, spiral, stunt, and total population densities and number of species) from early in the growing season (July), mid-season (August), or end of the season (October) were generally unrelated with soybean yield, with two exceptions (Table 11). Soybean yield was moderately negatively correlated ($r$ = -0.36; $P$ = 0.05; Table 11) with mid-season spiral nematode population densities indicating that the increase in spiral nematode population densities resulted in a decrease in soybean yield. In addition, soybean yield was weakly positively correlated ($r$ = 0.26; $P$ = 0.03; Table 11) with Stunt nematode population densities. The lack of correlation among nematode species at any of the three points in the growing season and soybean yield was likely due to the overall low nematode population densities throughout the entire study area in 2017 and 2018. Furthermore, no nematode assessed in this study reached above the critical threshold levels for soybean production in Arkansas to warrant concern that nematodes were a management problem in the study area (Kirkpatrick et al., 2014).

In contrast to the few correlations between soybean yield and nematode properties, numerous significant correlations existed between nematode species and early season soil properties in the top 10 cm. Soybean cyst nematode egg population density in August and October was negatively correlated with soil Ca ($r$ = -0.92;) and total soil C ($r$ = -0.37), respectively (Table 12). However, SCN egg population density in October was positively correlated with soil P ($r$ = 0.42), Fe ($r$ = 0.44), and Zn ($r$ = 0.94; Table 12). Soybean cyst J2 population density in July was negatively correlated with soil pH ($r$ = -0.66) and that from October was positively correlated with soil P ($r$ = 0.51; Table 12). Lance nematode population density in July was negatively correlated with clay content ($r$ = -0.74), while that from August was negatively correlated with soil pH ($r$ = -0.87) and that from October was negatively correlated with sand content (*r* = -0.35) and soil Na (*r* = -0.36; Table 12). However, lance nematode population density in July was positively correlated with silt content (*r* = 0.60), while that from August was positively correlated with soil BD (*r* = 0.72), soil Ca (*r* = 0.73), and SOM (*r* = 0.72) and that from October was positively correlated with soil K (*r* = 0.36) and soil Ca (*r* = 0.42; Table 12). Lesion nematode population density in August was negatively correlated with silt content (*r* = -0.95), soil S (*r* = -0.98), and soil Mn (*r* = -0.96), while that from October was negatively correlated with soil K (*r* = -0.45) and soil Cu (*r* = -0.48; Table 12). However, lesion nematode population density in July was positively correlated with soil Zn (*r* = 0.85), while that from August was positively correlated with soil Ca (*r* = 0.98) and that from October was positively correlated with total C (*r* = 0.72) and SOM (*r* = 0.467; Table 12). Spiral nematode population density in October was negatively correlated with soil S (*r* = -0.31), soil Zn (*r* = -0.49), and the C:N ratio (*r* = -0.35; Table 13). However, spiral nematode population density in July was positively correlated with silt content (*r* = 0.35) and soil Zn (*r* = 0.41), while that from August was positively correlated with soil Ca (*r* = 0.36), soil S (*r* = 0.45), and soil Na (*r* = 0.41) and that from October was positively correlated with soil pH (*r* = 0.35; Table 13). Stunt nematode population density in July was negatively correlated with silt content (*r* = -0.34), soil pH (*r* = -0.40), soil Mg (*r* = -0.26), and SOM (*r* = -0.27), while that from August was also negatively correlated with silt content (*r* = -0.40), soil pH (*r* = -0.31), and soil Mn (*r* = -0.29) and that from October was also negatively correlated with soil Mn (*r* = -0.30; Table 13). However, stunt nematode population density in July was positively correlated with soil S (*r* = 0.43), soil Fe (*r* = 0.37), and soil Cu (*r* = 0.29), while that from August was positively correlated with soil EC (*r* = 0.26) and also soil S (*r* = 0.31; Table 13). Total nematode population density in July was negatively correlated with silt content (*r* = -0.28), soil pH (*r* = -0.27), and SOM (*r* = -0.24), while that from August was also negatively correlated with silt content (*r* = -0.32), soil pH (*r* = -0.23), soil Mn (*r* = -0.27), and SOM (*r* = -0.23) and that from October was negatively correlated with soil EC (*r* = -0.26), soil P (*r* = -0.25), soil S (*r* = -0.31), soil Fe (*r* = -0.28), and soil Zn (*r* = -0.47; Table 13). However, total nematode population density in July was positively correlated with soil EC (*r* = 0.28), soil S (*r* = 0.38), and soil Fe (*r* = 0.40), while that from August was also positively correlated with soil EC (*r* = 0.32), soil S (*r* = 0.34), and soil Fe (*r* = 0.27) and that from October was positively correlated with soil Ca (*r* = 0.21) and soil Mg (*r* = 0.39; Table 13). Total nematode species present in the top 10 cm in July was negatively correlated with the soil C:N ratio (*r* = -0.24), while that from August was also negatively correlated with soil BD (*r* = -0.22), soil K (*r* = -0.23), and soil Ca (*r* = -0.28) and that from October was negatively correlated with soil EC (*r* = -0.32), soil P (*r* = -0.25), soil S (*r* = -0.22), soil Mn (*r* = -0.23), and soil Zn (*r* = -0.35; Table 13). However, total nematode species present in the top 10 cm in July was positively correlated with soil pH (*r* = 0.22), soil EC (*r* = 0.31), soil Na (*r* = 0.32), and soil B (*r* = 0.28), while that from August was also positively correlated with soil EC (*r* = 0.28) and soil P (*r* = 0.22; Table 13).

## Conclusions

Through assessing the natural nematode population densities in the soil on a wheat-soybean double-crop, this research has provided valuable understanding into the complexity of the effects of water and residue management on plant-parasitic nematodes. The objective of this investigation was to evaluate the combined long-term effects of tillage practice (conventional tillage and no-tillage), water management (irrigation and non-irrigation), residue burning (burned and non-burned), and wheat residue level (high and low) on the natural nematode population densities and reproduction in the top 10 cm within the growing season and between years soybean in a double-crop production system on a silt-loam soil in eastern Arkansas.

Wheat-soybean crop management affected nematode populations. The majority of nematodes studied were affected by at least one treatment or the interaction of two or more. Similar to what was hypothesized, nematodes population was generally greater under irrigation, CT, burn compared to dryland, NT, and nom-burn treatment, respectively. However, different treatment combinations did not have the same effect in all nematode species. Nematode management has to be tailored to species and agricultural practices for the best results.

**Acknowledgements**

The author would like to thank the Arkansas Soybean Promotion Board for partially financing this study. Ryder Anderson, Rebeca Anderson, Niyi Omidire, and Shelby Lebeau for providing field and laboratory assistance and the University of Arkansas System Division of Agriculture for supporting this research are gratefully acknowledged. The Andes Association of Cajamarca and Fulbright Peru for financing my master studies.

Table 1. Summary of typical management practices and their schedule (2017 and 2018) in the wheat-soybean double-crop production system at the Lon Mann Cotton Branch Experiment Station near Marianna, AR

| Agronomic activity | Approximate timing of activity |
|---|---|
| Wheat planting | Early November |
| Nitrogen fertilization of wheat | |
| First application | Early March |
| Split application | Early April |
| Wheat harvest | Early June |
| Residue burning | Early June |
| Conventional tillage | Early June |
| Soybean first planting | Early June |
| Soybean second planting | Early June |
| Irrigation Soybean harvest | Late October |

Table 2. Summary of the effects of irrigation (Irr), tillage (Till), residue burning (Burn), and residue level (Res) treatments, and their interactions on initial soil properties in the top 10 cm in May 2017 after 15 complete wheat-soybean cropping cycles on a silt-loam soil in eastern Arkansas. Bolded values were considered significant at $P < 0.05$.

| Source of variation | pH | EC | BD | P | K | Ca | Mg | S | Na | Fe | Mn | Zn | Cu | B | TN | TC | C:N | SOM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *P* | | | | | | | | | | | | | | | | | |
| Irr | **<0.01** | <0.01 | **0.02** | 0.05 | **<0.01** | <0.01 | <0.01 | **<0.01** | **<0.01** | <0.01 | 0.35 | 0.78 | <0.01 | <0.01 | 0.54 | 0.49 | 0.01 | 0.93 |
| Till | **<0.01** | 0.06 | 0.64 | 0.43 | 0.40 | <0.01 | **<0.01** | 0.45 | **0.04** | <0.01 | **0.04** | 0.34 | 0.62 | 0.03 | 0.59 | 0.63 | 0.75 | 0.91 |
| Irr*Till | 0.40 | 0.57 | 0.81 | 0.35 | 0.65 | 0.01 | 0.51 | 0.62 | 0.34 | 0.98 | 0.30 | 0.37 | 0.84 | 0.35 | 0.63 | 0.70 | **0.01** | 0.67 |
| Burn | **0.02** | 0.04 | 0.77 | 0.23 | 0.65 | 0.92 | 0.02 | 0.99 | **0.02** | 0.01 | **0.01** | **<0.01** | 0.19 | 0.05 | 0.41 | 0.46 | 0.57 | 0.03 |
| Irr*Burn | 0.81 | **0.04** | 0.19 | **0.01** | 0.10 | <0.01 | **0.03** | 0.47 | 0.85 | <0.01 | 0.80 | 0.23 | 0.90 | 0.31 | 0.86 | 0.87 | 0.88 | 0.02 |
| Till*Burn | 0.30 | 0.15 | 0.07 | 0.93 | 0.36 | 0.01 | 0.69 | 0.94 | 0.29 | 0.58 | 0.67 | 0.82 | 0.97 | 0.65 | 0.55 | 0.54 | 0.60 | 0.20 |
| Irr*Till*Burn | 0.96 | 0.81 | 0.71 | 0.68 | 0.69 | 0.12 | 0.53 | 0.35 | 0.57 | **0.03** | 0.25 | 0.25 | 0.09 | 0.68 | 0.54 | 0.60 | 0.52 | 0.47 |
| Res | 0.29 | 0.51 | 0.29 | **0.01** | 0.70 | 0.48 | 0.85 | 0.23 | 0.60 | 0.97 | 0.62 | 0.21 | 0.42 | 0.24 | 0.51 | 0.52 | 0.26 | 0.37 |
| Irr*Res | 0.40 | 0.50 | 0.11 | 0.19 | 0.46 | 0.87 | 0.88 | 0.44 | 0.94 | 0.62 | 0.98 | 0.20 | 0.08 | 0.39 | 0.58 | 0.55 | 0.08 | 0.31 |
| Till*Res | 0.73 | 0.51 | 0.53 | 1.00 | 0.77 | 0.11 | 0.67 | 0.35 | 0.35 | 0.87 | 0.61 | 0.77 | 0.12 | 0.17 | 0.67 | 0.72 | 0.68 | 0.91 |
| Irr*Till*Res | 0.10 | 0.30 | 0.20 | 0.68 | 0.41 | 0.26 | 0.83 | 0.61 | 0.39 | 0.40 | 0.82 | 0.48 | 0.87 | 0.45 | 0.51 | 0.49 | 0.07 | 0.08 |
| Burn*Res | 1.00 | 0.20 | 0.55 | 0.65 | 0.94 | 0.96 | 0.94 | 0.85 | 0.23 | 0.76 | 0.73 | 0.64 | 0.91 | 0.40 | 0.66 | 0.64 | 0.57 | 0.75 |
| Irr*Burn*Res | 0.33 | 0.20 | 0.46 | 0.39 | 0.31 | 0.07 | 0.92 | 0.62 | 0.72 | 0.23 | 0.30 | 0.63 | 0.70 | 0.26 | 0.69 | 0.65 | 0.05 | 0.87 |
| Till*Burn*Res | 0.12 | 0.61 | 0.39 | 0.51 | 0.62 | 0.01 | 0.52 | 0.86 | 0.43 | 0.46 | 0.77 | 0.08 | 0.14 | 0.32 | 0.73 | 0.66 | **0.02** | 0.92 |
| Irr*Till*Burn*Res | 0.66 | 0.43 | 0.21 | 0.78 | 0.93 | **<0.01** | 0.18 | 0.46 | 0.88 | 0.37 | 0.91 | 0.45 | **0.01** | **0.03** | 0.87 | 0.88 | 0.42 | **0.03** |

Table 3. Extractable soil calcium (Ca), copper (Cu), and boron (B) content and soil organic matter (SOM) concentration differences among irrigation (irrigated and dryland)-tillage [conventional tillage (CT) and no-tillage (NT)]-burning (burn and no burn)-residue level (high and low) treatment combinations after 15 cropping cycles in a long-term wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Irrigation | Tillage | Burning | Residue level | Ca ($kg\ ha^{-1}$) | | Cu ($kg\ ha^{-1}$) | | B ($kg\ ha^{-1}$) | | SOM (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Irrigated | CT | Burn | High | 1727 | c[a] | 1.5 | bc[a] | 1.3 | ab[a] | 2.3 | abcd[a] |
| | | | Low | 1805 | b | 1.5 | bc | 1.3 | ab | 2.5 | a |
| | | No burn | High | 1572 | de | 1.2 | c | 1.4 | a | 2.4 | abcd |
| | | | Low | 1463 | fg | 1.8 | ab | 1.3 | ab | 2.1 | abcd |
| | NT | Burn | High | 1699 | c | 1.2 | c | 1.3 | ab | 2.5 | abc |
| | | | Low | 1603 | d | 1.6 | abc | 1.2 | b | 1.9 | cd |
| | | No burn | High | 1257 | h | 1.8 | ab | 1.3 | ab | 2.4 | abc |
| | | | Low | 1404 | g | 1.5 | bc | 1.3 | ab | 2.3 | abcd |
| Dryland | CT | Burn | High | 1601 | d | 1.6 | abc | 0.9 | c | 2.3 | abcd |
| | | | Low | 1599 | d | 1.7 | abc | 0.6 | e | 2 | bcd |
| | | No burn | High | 1938 | a | 1.9 | ab | 0.8 | cde | 2.5 | ab |
| | | | Low | 1942 | a | 1.9 | ab | 0.8 | cd | 2.5 | abc |
| | NT | Burn | High | 1512 | ef | 2.1 | a | 0.6 | e | 1.9 | d |
| | | | Low | 1564 | de | 1.7 | abc | 0.6 | de | 2.3 | abcd |
| | | No burn | High | 1848 | b | 1.9 | ab | 0.7 | cde | 2.6 | a |
| | | | Low | 1811 | b | 1.8 | ab | 0.7 | cde | 2.6 | a |

[a] Means followed by different letters in the same column are different at $P < 0.05$.

Table 4. Summary of the effects of year (Year), sample date within the growing season (Date), irrigation (Irr), tillage (Till), residue burning (Burn), residue level (Res) treatments and their interactions on soybean cyst nematode (SCN) eggs and stage 2 juveniles (J2), lance, lesion, spiral, and stunt nematode species, and total (Total) nematode population densities in the top 10 cm of soil in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Bolded values were considered significant at $P < 0.05$.

| Source of variation | SCN eggs | SCN | Lance | Lesion | Spiral | Stunt | Total |
|---|---|---|---|---|---|---|---|
| | *P* | | | | | | |
| Year | 0.57 | <0.01 | 0.05 | 0.99 | <0.01 | <0.01 | <0.01 |
| Irr | 0.1 | <0.01 | <0.01 | 0.72 | <0.01 | 0.05 | 0.85 |
| Year*Irr | 0.11 | 0.97 | 0.06 | 0.79 | 0.03 | 0.13 | **0.03** |
| Till | 0.21 | 0.18 | 0.48 | **0.02** | <0.01 | 0.62 | 0.65 |
| Year*Till | 0.2 | 0.21 | 0.66 | 0.68 | 0.54 | 0.1 | 0.19 |
| Irr*Till | 0.57 | 0.31 | **0.03** | 0.91 | 0.35 | 0.04 | 0.06 |
| Year*Irr*Till | 0.31 | **0.03** | 0.34 | 0.25 | **<0.01** | 0.45 | 0.88 |
| Burn | 0.48 | 0.88 | 0.96 | 0.06 | 0.07 | <0.01 | <0.01 |
| Year*Burn | 0.25 | 0.52 | 0.33 | 0.09 | 0.89 | <0.01 | <0.01 |
| Irr*Burn | 0.2 | 0.1 | 0.22 | **0.02** | 0.35 | 0.45 | 0.14 |
| Year*Irr*Burn | 0.31 | 0.99 | 0.83 | 0.15 | 0.21 | 0 | 0.2 |
| Till*Burn | 0.84 | **<0.01** | 0.95 | 0.4 | 0.81 | 0.1 | 0.08 |
| Year*Till*Burn | 0.05 | 0.6 | 0.72 | 0.66 | 0.71 | 0.98 | 0.24 |
| Irr*Till*Burn | **0.01** | 0.22 | 0.7 | 0.82 | 0.18 | 0.21 | **0.02** |
| Year*Irr*Till*Burn | 0.7 | 0.31 | 0.32 | 0.23 | 0.39 | **0.02** | 0.64 |
| Res | 0.26 | 0.55 | 0.28 | 0.39 | 0.18 | 0.83 | 0.36 |
| Year*Res | 0.07 | 0.08 | 0.5 | 0.13 | 0.94 | 0.25 | 0.82 |
| Irr*Res | 0.64 | 0.16 | 0.61 | 0.85 | 0.09 | 0.56 | 0.59 |
| Year*Irr*Res | 0.54 | 0.13 | 0.24 | 0.56 | **<0.05** | 0 | 0.08 |
| Till*Res | 0.32 | 0.89 | 0.33 | 0.57 | 0.71 | 0.18 | 0.28 |
| Year*Till*Res | 0.21 | 0.54 | 0.66 | 0.3 | 0.48 | 0.44 | 0.99 |
| Irr*Till*Res | 0.51 | 0.71 | 0.39 | 0.78 | 0.79 | 0 | 0.47 |
| Year*Irr*Till*Res | 0.99 | 0.17 | 0.71 | 0.46 | 0.68 | **0.01** | 0.63 |
| Burn*Res | 0.51 | 0.57 | 0.76 | 0.13 | 0.36 | 0.03 | 0.19 |
| Year*Burn*Res | 0.26 | 0.65 | 0.93 | 0.44 | 0.11 | 0.78 | 0.38 |
| Irr*Burn*Res | 0.39 | 0.1 | 0.77 | 0.41 | 0.16 | 0.41 | 0.98 |
| Year*Irr*Burn*Res | 0.4 | 0.74 | 0.53 | 0.81 | 0.07 | **<0.01** | 0.14 |
| Till*Burn*Res | 0.87 | 0.82 | 0.14 | 0.66 | 0.77 | 0.15 | 0.98 |
| Year*Till*Burn*Res | 0.15 | 0.63 | 0.18 | 0.99 | 0.29 | 0.87 | 0.8 |
| Irr*Till*Burn*Res | 0.44 | 0.31 | 0.4 | 0.96 | **0.02** | **<0.01** | 0.68 |
| Year*Irr*Till*Burn*Res | 0.4 | 0.55 | 0.83 | 0.7 | 0.05 | 0.05 | 0.06 |

Table 4. Continued

| Source of variation | SCN eggs | SCN | Lance | Lesion | Spiral | Stunt | Total |
|---|---|---|---|---|---|---|---|
| | | | | *P* | | | |
| Date | **<0.05** | 0.64 | 0.07 | 0.14 | 0.08 | 0.09 | 0.03 |
| Year*Date | 0.48 | 0.68 | 0.11 | 0.42 | 0.09 | 0.09 | 0.01 |
| Irr*Date | 0.3 | 0.23 | 0.09 | 0.71 | 0.08 | 0.09 | 0.18 |
| Year*Irr*Date | 0.13 | 0.25 | 0.24 | 0.66 | 0.1 | 0.12 | 0.05 |
| Till*Date | 0.34 | 0.4 | 0.31 | 0.18 | 0.21 | 0.11 | 0.06 |
| Year*Till*Date | 0.3 | 0.43 | 0.62 | 0.28 | 0.19 | 0.14 | 0.15 |
| Irr*Till*Date | 0.23 | 0.36 | 0.88 | 0.43 | 0.16 | 0.19 | 0.05 |
| Year*Irr*Till*Date | 0.23 | 0.31 | 0.62 | 0.6 | 0.5 | 0.19 | 0.13 |
| Burn*Date | 0.4 | 0.89 | 0.61 | 0.6 | 0.33 | 0.07 | 0.05 |
| Year*Burn*Date | 0.09 | 0.32 | 0.76 | 0.34 | 0.14 | 0.11 | 0.04 |
| Irr*Burn*Date | 0.6 | 0.16 | 0.65 | 0.3 | 0.25 | 0.18 | 0.35 |
| Year*Irr*Burn*Date | 0.42 | 0.33 | 0.32 | 0.32 | 0.91 | 0.68 | 0.2 |
| Till*Burn*Date | 0.45 | 0.35 | 0.4 | 0.62 | 0.36 | 0.31 | 0.18 |
| Year*Till*Burn*Date | 0.31 | 0.27 | 0.2 | 0.36 | 0.83 | 0.08 | **0.04** |
| Irr*Till*Burn*Date | 0.58 | 0.54 | 0.86 | 0.9 | 0.29 | 0.19 | 0.2 |
| Year*Irr*Till*Burn*Date | 0.43 | 0.23 | 0.3 | 0.55 | 0.19 | 0.14 | 0.14 |
| Res*Date | 0.7 | 0.23 | 0.25 | 0.68 | 0.23 | 0.29 | 0.17 |
| Year*Res*Date | 0.23 | 0.51 | 0.52 | 0.21 | 0.19 | 0.32 | 0.07 |
| Irr*Res*Date | 0.54 | 0.28 | 0.36 | 0.22 | 0.42 | 0.19 | 0.11 |
| Year*Irr*Res*Date | 0.1 | 0.41 | 0.69 | 0.61 | 0.25 | 0.09 | 0.1 |
| Till*Res*Date | 0.17 | 0.42 | 0.42 | 0.59 | 0.34 | 0.13 | 0.44 |
| Year*Till*Res*Date | 0.5 | 0.35 | 0.32 | 0.31 | 0.2 | 0.1 | 0.13 |
| Irr*Till*Res*Date | 0.69 | 0.17 | 0.23 | 0.4 | 0.76 | 0.2 | 0.32 |
| Year*Irr*Till*Res*Date | 0.24 | 0.19 | 0.36 | 0.3 | 0.44 | 0.49 | 0.11 |
| Burn*Res*Date | 0.15 | 0.21 | 0.53 | 0.4 | 0.94 | 0.14 | 0.25 |
| Year*Burn*Res*Date | 0.38 | 0.1 | 0.29 | 0.28 | 0.15 | 0.13 | 0.21 |
| Irr*Burn*Res*Date | 0.23 | 0.5 | 0.18 | 0.26 | 0.59 | 0.5 | 0.07 |
| Year*Irr*Burn*Res*Date | 0.19 | 0.53 | 0.27 | 0.4 | 0.98 | 0.08 | 0.08 |
| Till*Burn*Res*Date | 0.19 | 0.48 | 0.26 | 0.34 | 0.36 | 0.56 | 0.17 |
| Year*Till*Burn*Res*Date | 0.15 | 0.22 | 0.25 | 0.39 | 0.43 | 0.19 | 0.26 |
| Irr*Till*Burn*Res*Date | 0.25 | 0.23 | 0.78 | 0.6 | 0.22 | 0.09 | 0.09 |
| Year*Irr*Till*Burn*Res*Date | 0.18 | 0.1 | 0.41 | 0.24 | 0.18 | 0.11 | 0.08 |

Table 5. Spiral nematode concentration differences among irrigation-tillage [conventional tillage (CT) and no-tillage (NT)]-residue burning-residue level treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Irrigation | Tillage | Burning | Residue level | Nematode concentration [Number $(100\ cm^3)^{-1}$] | |
|---|---|---|---|---|---|
| Irrigated | CT | Burn | High | 15.4 | ab[a] |
| | | | Low | 21.1 | a |
| | | No burn | High | 23 | a |
| | | | Low | 24.6 | a |
| | NT | Burn | High | 14.5 | ab |
| | | | Low | 2.3 | abcde |
| | | No burn | High | 0.8 | def |
| | | | Low | 6.0 | abcd |
| Dryland | CT | Burn | High | 7.0 | abc |
| | | | Low | 1.5 | cde |
| | | No burn | High | 0.8 | cdef |
| | | | Low | 0.3 | ef |
| | NT | Burn | High | 0.9 | cdef |
| | | | Low | 0.6 | ef |
| | | No burn | High | 1.3 | cde |
| | | | Low | 0.1 | f |

[a] Means followed by different letters in the same column are different at $P < 0.05$.

Table 6. Stunt nematode concentration differences among year-irrigation-tillage [conventional tillage (CT) and no-tillage (NT)]-residue burning treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Year | Irrigation | Tillage | Burning | Nematode concentration [Number (100 $cm^3)^{-1}$] | |
|---|---|---|---|---|---|
| 2017 | Irrigated | CT | Burn | 100.6 | ab[a] |
| | | | No burn | 17.4 | cde |
| | | NT | Burn | 233.3 | a |
| | | | No burn | 5.9 | e |
| | Dryland | CT | Burn | 123.9 | ab |
| | | | No burn | 28.4 | cd |
| | | NT | Burn | 209.6 | a |
| | | | No burn | 100.3 | ab |
| 2018 | Irrigated | CT | Burn | 21.7 | cd |
| | | | No burn | 31.8 | cd |
| | | NT | Burn | 15.4 | de |
| | | | No burn | 18.5 | cde |
| | Dryland | CT | Burn | 27.0 | cd |
| | | | No burn | 20.6 | cd |
| | | NT | Burn | 46.3 | bc |
| | | | No burn | 12.6 | de |

[a] Means followed by different letters in the same column are different at $P < 0.05$.

Table 7. Stunt nematode concentration differences among year-irrigation-tillage [conventional tillage (CT) and no-tillage (NT)]-residue level treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Year | Irrigation | Tillage | Residue level | Nematode concentration [Number $(100\ cm^3)^{-1}$] | |
|---|---|---|---|---|---|
| 2017 | Irrigated | CT | High | 29.9 | defg[a] |
| | | | Low | 58.6 | abcd |
| | | NT | High | 19.9 | efgh |
| | | | Low | 69.1 | abcd |
| | Dryland | CT | High | 102.3 | abc |
| | | | Low | 34.4 | defg |
| | | NT | High | 156.0 | a |
| | | | Low | 134.8 | ab |
| 2018 | Irrigated | CT | High | 25.0 | defg |
| | | | Low | 27.7 | defg |
| | | NT | High | 40.6 | cdef |
| | | | Low | 7.0 | h |
| | Dryland | CT | High | 35.1 | def |
| | | | Low | 15.7 | 1fgh |
| | | NT | High | 11.6 | hg |
| | | | Low | 50.3 | bcde |

[a] Means followed by different letters in the same column are different at $P < 0.05$.

Table 8. Stunt nematode concentration differences among year-irrigation-residue burning-residue level treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Year | Irrigation | Burning | Residue level | Nematode concentration [Number (100 $cm^3$)$^{-1}$] | |
|---|---|---|---|---|---|
| 2017 | Irrigated | Burn | High | 163.4 | a[a] |
| | | | Low | 143.6 | a |
| | | No burn | High | 3.7 | f |
| | | | Low | 28.2 | cd |
| | Dryland | Burn | High | 178.5 | a |
| | | | Low | 145.6 | a |
| | | No burn | High | 89.5 | ab |
| | | | Low | 31.9 | bc |
| 2018 | Irrigated | Burn | High | 27.4 | cd |
| | | | Low | 12.2 | def |
| | | No burn | High | 37.0 | bc |
| | | | Low | 15.9 | cde |
| | Dryland | Burn | High | 46.6 | bc |
| | | | Low | 26.7 | cd |
| | | No burn | High | 8.8 | ef |
| | | | Low | 29.7 | cd |

[a] Means followed by different letters in the same column are different at $P < 0.05$.

Table 9. Stunt nematode concentration differences among irrigation-tillage [conventional tillage (CT) and no-tillage (NT)]-residue burning-residue level treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Irrigation | Tillage | Burning | Residue level | Nematode concentration [Number (100 $cm^3$)$^{-1}$] | |
|---|---|---|---|---|---|
| Irrigated | CT | Burn | High | 63.6 | ab[a] |
| | | | Low | 34.4 | bc |
| | | No burn | High | 11.8 | d |
| | | | Low | 47.1 | b |
| | NT | Burn | High | 70.5 | ab |
| | | | Low | 51.0 | ab |
| | | No burn | High | 11.8 | d |
| | | | Low | 9.5 | d |
| Dryland | CT | Burn | High | 63.9 | ab |
| | | | Low | 52.1 | ab |
| | | No burn | High | 56.3 | ab |
| | | | Low | 10.4 | d |
| | NT | Burn | High | 130.4 | a |
| | | | Low | 74.5 | ab |
| | | No burn | High | 13.9 | cd |
| | | | Low | 91.0 | ab |

[a] Means followed by different letters in the same column are different at $P < 0.05$.

Table 10. Total nematode concentration differences among year-tillage [conventional tillage (CT) and no-tillage (NT)]-residue burning-sampling date within the growing season treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Year | Tillage | Burning | Sample date | Nematode concentration [Number (100 $cm^3$)$^{-1}$] | |
|---|---|---|---|---|---|
| 2017 | CT | Burn | July | 233.8 | b[a] |
| | | | August | 176.8 | bcd |
| | | | October | 152.5 | cde |
| | | No burn | July | 211.5 | bc |
| | | | August | 81.l | ghijk |
| | | | October | 72.0 | hijkl |
| | NT | Burn | July | 413.6 | a |
| | | | August | 402.6 | a |
| | | | October | 126.8 | def |
| | | No burn | July | 115.4 | ef |
| | | | August | 84.5 | ghij |
| | | | October | 93.7 | fghi |
| 2018 | CT | Burn | July | 57.9 | jklm |
| | | | August | 49.5 | lm |
| | | | October | 248.6 | b |
| | | No burn | July | 86.5 | fghi |
| | | | August | 50.8 | lm |
| | | | October | 227.0 | b |
| | NT | Burn | July | 45.4 | m |
| | | | August | 56.9 | klm |
| | | | October | 259.6 | b |
| | | No burn | July | 95.6 | fgh |
| | | | August | 64.4 | ijklm |
| | | | October | 110.6 | efg |

[a] Means followed by different letters in the same column are different at $P < 0.05$.

Table 11. Summary of correlation coefficients (*r*) between nematode species and soybean yield across 2017 and 2018 in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Nematode Property | July | August | October |
|---|---|---|---|
| | | ——— r ——— | |
| SCN eggs | 0.55 | -0.82 | 0.27 |
| SCN J2 | 0.33 | 0.02 | 0.31 |
| Lance | 0.42 | 0.60 | -0.15 |
| Lesion | -0.09 | -0.66 | 0.28 |
| Spiral | -0.35 | -0.36* | 0.16 |
| Stunt | 0.18 | 0.26* | -0.22 |
| Total | 0.14 | 0.17 | -0.05 |
| Species | 0.08 | 0.04 | -0.04 |

* $P \leq 0.05$

Table 12. Summary of correlation coefficients (*r*) between nematode population densities and soil properties from the top 10 cm across 2017 and 2018 in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Soil property | SCN eggs | | | SCN J2 | | | Lance | | | Lesion | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | July | August | October | July | August | October | July | August | October | July | August | October |
| | | | | | | *r* | | | | | | |
| Sand | -0.48 | 0.2 | -0.06 | 0.11 | 0.15 | -0.25 | 0.11 | -0.6 | -0.35* | 0.18 | -0.65 | 0.04 |
| Silt | 0.34 | 0.69 | -0.22 | -0.4 | -0.26 | 0.23 | 0.6** | -0.29 | 0.16 | -0.14 | -0.95* | 0.35 |
| Clay | 0.28 | -0.69 | 0.21 | 0.22 | 0.07 | 0 | -0.74*** | 0.58 | 0.12 | -0.12 | 0.94 | -0.28 |
| pH | -0.06 | 0.56 | -0.27 | -0.66 | -0.16 | -0.23 | -0.12 | -0.87* | 0.09 | 0.17 | -0.86 | 0.23 |
| EC | -0.54 | -0.14 | 0.21 | 0.12 | -0.41 | -0.03 | -0.23 | -0.12 | 0.08 | 0.37 | -0.33 | -0.08 |
| BD | 0.15 | -0.73 | -0.33 | 0.05 | 0.03 | -0.17 | -0.43 | 0.72* | 0.01 | . | 0.82 | -0.38 |
| P | -0.16 | 0.53 | 0.42* | -0.17 | -0.23 | 0.51* | -0.17 | 0.17 | 0.21 | 0.19 | -0.39 | 0.19 |
| K | -0.01 | -0.34 | 0.01 | -0.11 | 0.03 | 0.1 | 0.15 | 0.53 | 0.36* | -0.74 | 0.7 | -0.45* |
| Ca | -0.81 | -0.92* | -0.11 | -0.16 | 0.38 | 0.09 | -0.23 | 0.73* | 0.42* | 0.1 | 0.97* | 0.19 |
| Mg | -0.4 | -0.83 | -0.17 | -0.41 | 0.3 | -0.03 | -0.26 | 0.05 | 0.05 | -0.11 | 0.92 | 0.21 |
| S | -0.3 | 0.48 | 0.28 | 0.24 | -0.38 | 0.22 | -0.27 | 0.15 | -0.16 | 0.13 | -0.98* | -0.06 |
| Na | -0.37 | -0.15 | 0.15 | -0.15 | -0.2 | -0.14 | -0.27 | -0.23 | -0.36* | 0.27 | -0.22 | -0.27 |
| Fe | -0.02 | -0.45 | 0.44* | -0.15 | 0.33 | 0.37 | -0.06 | 0.63 | -0.1 | -0.11 | 0.5 | -0.34 |
| Mn | 0.61 | 0.52 | -0.33 | -0.3 | -0.22 | 0.05 | -0.35 | 0.14 | 0.2 | 0.04 | -0.96* | 0.19 |
| Zn | -0.05 | 0.94* | 0.2 | -0.06 | -0.43 | 0.14 | -0.14 | -0.07 | 0.29 | 0.85** | -0.82 | 0.13 |
| Cu | 0.57 | 0.58 | 0.02 | -0.23 | -0.14 | 0.22 | -0.14 | 0.34 | 0.14 | -0.33 | 0.65 | -0.48* |
| B | -0.22 | 0.15 | -0.05 | 0.16 | -0.47 | -0.08 | -0.14 | -0.47 | -0.19 | 0.67 | -0.32 | -0.3 |
| Total C | -0.21 | -0.3 | -0.37* | 0.33 | -0.08 | -0.14 | 0.44 | 0.34 | 0.31 | 0.34 | -0.87 | 0.72*** |
| C:N | -0.13 | 0.42 | -0.1 | 0.46 | -0.35 | -0.04 | -0.05 | -0.11 | 0.31 | 0.56 | -0.38 | 0.02 |
| SOM | -0.21 | -0.54 | -0.27 | 0.25 | 0.09 | 0.05 | 0.39 | 0.72* | 0.3 | 0.34 | -0.82 | 0.67* |

* $P \leq 0.05$; ** $P < 0.01$; *** $P < 0.001$

Table 13. Summary of correlation coefficients (*r*) between nematode population densities and soil properties from the top 10 cm across 2017 and 2018 in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Soil property | Spiral | | | Stunt | | | Total nematode | | | Species | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | July | August | October | July | August | October | July | August | October | July | August | October |
| | *r* | | | | | | | | | | | |
| Sand | -0.15 | -0.24 | 0.16 | 0.11 | 0.15 | 0 | 0.06 | 0.09 | -0.01 | 0.08 | 0.01 | 0.05 |
| Silt | 0.35* | -0.14 | -0.09 | -0.34 | -0.40*** | -0.15 | -0.23* | -0.32** | -0.16 | 0.01 | 0.08 | -0.16 |
| Clay | -0.13 | 0.27 | -0.06 | 0.17 | 0.18 | 0.13 | 0.12 | 0.17 | 0.12 | -0.07 | -0.07 | 0.08 |
| pH | 0.23 | 0.04 | 0.35* | -0.4 | -0.31** | -0.12 | -0.27** | -0.23* | 0.07 | 0.22* | 0.11 | -0.19 |
| EC | 0.26 | 0.34 | -0.21 | 0.19 | 0.26 | 0.15 | 0.28** | 0.32** | -0.26* | 0.31 | 0.28** | -0.32** |
| BD | -0.29 | -0.25 | 0.17 | 0.06 | 0.01 | 0.09 | -0.02 | -0.06 | 0.17 | -0.09 | -0.22* | 0.03 |
| P | 0.16 | 0.2 | -0.18 | 0.13 | 0.15 | -0.16 | 0.21 | 0.2 | -0.25* | 0.2 | 0.22* | -0.25* |
| K | -0.25 | -0.08 | -0.14 | 0.11 | -0.06 | -0.01 | 0.08 | -0.1 | 0.09 | -0.08 | -0.23* | 0.1 |
| Ca | -0.06 | 0.36* | 0.14 | -0.09 | -0.09 | 0.01 | -0.05 | -0.07 | 0.21* | 0 | -0.28** | -0.03 |
| Mg | -0.12 | 0.34 | 0.54*** | -0.26* | -0.16 | -0.05 | -0.16 | -0.1 | 0.39*** | 0.15 | -0.12 | 0.03 |
| S | 0.23 | 0.45* | -0.31* | 0.43*** | 0.31** | 0.11 | 0.38*** | 0.34** | -0.31* | 0.2 | 0.28 | -0.22* |
| Na | 0.22 | 0.41* | 0.17 | 0.14 | 0.04 | 0.15 | 0.18 | 0.08 | -0.13 | 0.32 | 0.03 | -0.17 |
| Fe | 0 | 0.34 | -0.19 | 0.37 | 0.22 | -0.13 | 0.40*** | 0.27* | -0.28* | 0.19 | 0.08 | -0.19 |
| Mn | 0.31 | -0.16 | -0.01 | -0.19 | -0.29* | -0.30* | -0.13 | -0.27* | -0.22 | 0.05 | 0.05 | -0.23* |
| Zn | 0.41* | -0.05 | -0.49*** | 0.1 | 0.01 | -0.08 | 0.18 | 0.05 | -0.47*** | 0.17 | 0.26 | -0.35** |
| Cu | -0.16 | -0.32 | 0.04 | 0.29* | 0.02 | -0.16 | 0.22 | -0.02 | -0.03 | -0.08 | 0 | 0.04 |
| B | 0.31 | 0.24 | -0.18 | -0.1 | 0.06 | 0.2 | -0.01 | 0.12 | -0.12 | 0.28** | 0.26 | -0.06 |
| Total C | -0.1 | 0.13 | -0.11 | -0.31 | -0.15 | 0 | -0.14 | -0.14 | -0.1 | -0.13 | -0.09 | -0.12 |
| C:N | 0.28 | -0.08 | -0.35* | -0.16 | -0.02 | 0.03 | -0.16 | -0.11 | 0.02 | -0.24* | -0.11 | 0.2 |
| SOM | 0.07 | 0.18 | -0.17 | -0.27* | -0.3 | -0.07 | -0.24* | -0.23* | -0.01 | -0.15 | -0.12 | -0.03 |

* $P \leq 0.05$; ** $P < 0.01$; *** $P < 0.001$

Table 14. Summary of monthly soil and air temperature, total rainfall during the soybean-growing season in 2017 and 2018 in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas and the 30-year mean monthly rainfall and air temperature.

| Year | Month | Soil max (°C) | Soil min (°C) | Soil mean (°C) | Air Max (°C) | Air Min (°C) | Air mean (°C) | 30-year mean air (°C) | % diff | Precipitation (cm) | Precipitation (cm) | 30-year mean (cm) | % diff |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2017 | May | 26.7 | 19.7 | 23.2 | 27.0 | 15.5 | 21.3 | 21.3 | -0.1 | 17.27 | 17.3 | 58.8 | -70.6 |
| | June | 31.7 | 24.1 | 27.9 | 30.2 | 19.8 | 25.0 | 25.7 | -2.8 | 17.3 | 34.6 | 68.8 | -49.7 |
| | July | 34.5 | 27.9 | 31.2 | 32.5 | 21.9 | 27.2 | 27.2 | 0.1 | 14.63 | 49.2 | 78.3 | -37.2 |
| | August | 32.4 | 26.3 | 29.4 | 30.2 | 20.9 | 25.6 | 26.6 | -3.9 | 17.93 | 67.1 | 85.0 | -21.0 |
| | September | 29.3 | 23.2 | 26.3 | 28.7 | 17.6 | 23.2 | 22.8 | 1.5 | 15.54 | 82.7 | 91.4 | -9.6 |
| | October | 23.2 | 18.7 | 21.0 | 24.5 | 11.6 | 18.1 | 16.8 | 7.5 | 6.83 | 89.5 | 101.9 | -12.2 |
| | 6-month period | 29.6 | 23.3 | 26.5 | 28.9 | 17.9 | 23.4 | 23.4 | 0.4 | 89.5 | 340.34 | 484.2 | -29.7 |
| 2018 | May | 29.9 | 21.7 | 25.8 | 31.6 | 19.0 | 25.3 | 21.3 | 18.8 | 3.61 | 3.6 | 58.8 | -93.9 |
| | June | 33.9 | 25.9 | 29.9 | 32.9 | 21.4 | 27.1 | 25.7 | 5.6 | 7.77 | 11.4 | 68.8 | -83.5 |
| | July | 35.9 | 28.6 | 32.2 | 33.7 | 22.4 | 28.1 | 27.2 | 3.3 | 4.27 | 15.7 | 78.3 | -80.0 |
| | August | 32.4 | 25.7 | 29.0 | 31.5 | 20.7 | 26.1 | 26.6 | -1.8 | 11.33 | 27.0 | 85.0 | -68.3 |
| | September | 29.8 | 24.2 | 27.0 | 29.2 | 19.7 | 24.5 | 22.8 | 7.1 | 22.6 | 49.6 | 91.4 | -45.8 |
| | October | 23.0 | 18.0 | 20.5 | 23.4 | 12.5 | 18.0 | 16.8 | 6.7 | 12.09 | 61.7 | 101.9 | -39.5 |
| | 6-month period | 30.8 | 24.0 | 27.4 | 30.4 | 19.3 | 24.8 | 23.4 | 6.6 | 61.67 | 168.87 | 484.2 | -65.1 |

Table 15. Summary of soil moisture content during soybean-growing season in 2018 in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas.

| Plot | Treatment | | | | Soil Moisture ($cm^3$/ $cm^3$) | |
|---|---|---|---|---|---|---|
| | Tillage | Burning | Residue | Irrigation | August | October |
| 1 | CT | No burn | High | Irrigated | 0.04 | 0.47 |
| 2 | NT | No burn | Low | Irrigated | 0.06 | 0.43 |
| 3 | NT | No burn | High | Irrigated | 0.07 | 0.40 |
| 4 | CT | No burn | Low | Irrigated | 0.11 | 0.37 |
| 5 | NT | No burn | Low | Irrigated | 0.10 | 0.38 |
| 6 | CT | No burn | High | Irrigated | 0.07 | 0.33 |
| 7 | CT | No burn | Low | Irrigated | 0.07 | 1.39 |
| 8 | NT | No burn | High | Irrigated | 0.00 | 0.31 |
| 9 | NT | No burn | Low | Irrigated | 0.02 | 0.42 |
| 10 | CT | No burn | High | Irrigated | 0.12 | 0.44 |
| 11 | NT | No burn | High | Irrigated | 0.06 | 0.34 |
| 12 | CT | No burn | Low | Irrigated | 0.08 | 0.27 |
| 13 | CT | Burn | Low | Irrigated | 0.11 | 0.33 |
| 14 | NT | Burn | Low | Irrigated | 0.07 | 0.33 |
| 15 | NT | Burn | High | Irrigated | 0.08 | 0.29 |
| 16 | CT | Burn | Low | Irrigated | 0.17 | 0.43 |
| 17 | NT | Burn | High | Irrigated | 0.03 | 0.34 |
| 18 | CT | Burn | Low | Irrigated | 0.10 | 0.40 |
| 19 | CT | Burn | High | Irrigated | 0.12 | 0.52 |
| 20 | NT | Burn | High | Irrigated | 0.02 | 0.24 |
| 21 | NT | Burn | Low | Irrigated | 0.04 | 0.38 |
| 22 | CT | Burn | High | Irrigated | 0.12 | 0.38 |
| 23 | NT | Burn | Low | Irrigated | 0.02 | 0.40 |
| 24 | CT | Burn | High | Irrigated | 0.08 | 0.37 |
| 25 | CT | Burn | High | Dryland | 0.05 | 0.51 |
| 26 | NT | Burn | High | Dryland | 0.04 | 0.27 |
| 27 | NT | Burn | High | Dryland | 0.05 | 0.30 |
| 28 | CT | Burn | Low | Dryland | 0.04 | 0.36 |
| 29 | NT | Burn | High | Dryland | 0.05 | 0.32 |
| 30 | CT | Burn | Low | Dryland | 0.05 | 0.31 |
| 31 | CT | Burn | Low | Dryland | 0.05 | 0.33 |
| 32 | NT | Burn | Low | Dryland | 0.05 | 0.37 |
| 33 | NT | Burn | Low | Dryland | 0.05 | 0.26 |
| 34 | CT | Burn | High | Dryland | 0.08 | 0.42 |
| 35 | NT | Burn | Low | Dryland | 0.06 | 0.36 |
| 36 | CT | Burn | High | Dryland | 0.05 | 0.32 |
| 37 | CT | No burn | High | Dryland | 0.05 | 0.41 |
| 38 | NT | No burn | Low | Dryland | 0.08 | 0.32 |
| 39 | NT | No burn | High | Dryland | 0.08 | 0.30 |
| 40 | CT | No burn | High | Dryland | 0.07 | 0.34 |
| 41 | NT | No burn | Low | Dryland | 0.06 | 0.44 |
| 42 | CT | No burn | High | Dryland | 0.05 | 0.36 |
| 43 | CT | No burn | Low | Dryland | 0.06 | 0.27 |
| 44 | NT | No burn | High | Dryland | 0.07 | 0.35 |
| 45 | NT | No burn | Low | Dryland | 0.07 | 0.36 |
| 46 | CT | No burn | Low | Dryland | 0.06 | 0.30 |
| 47 | NT | No burn | High | Dryland | 0.08 | 0.42 |
| 48 | CT | No burn | Low | Dryland | 0.04 | 0.35 |

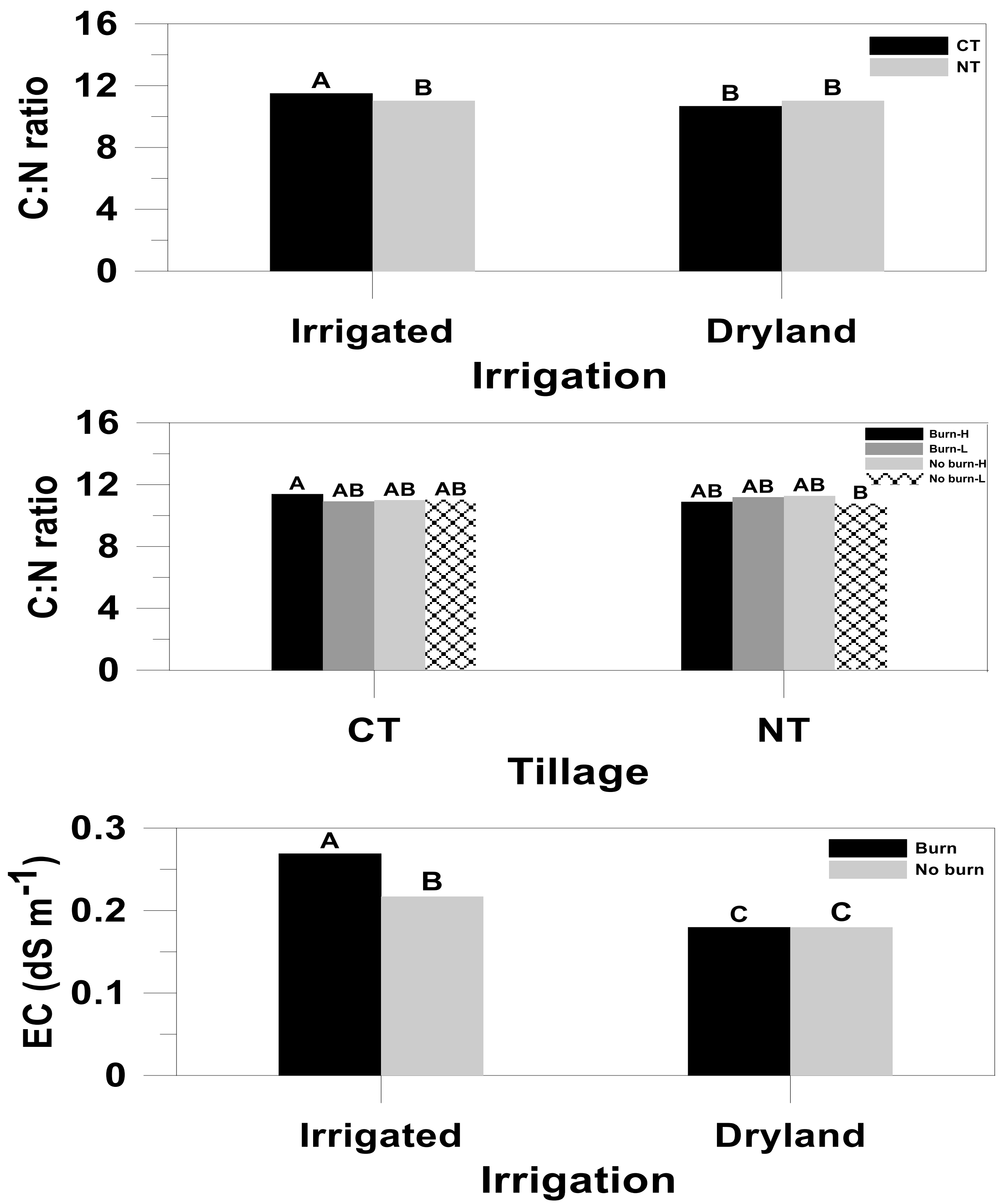


Figure 1. Soil C:N ratio differences among irrigation (irrigated and dryland) and tillage [conventional tillage (CT) and no-tillage (NT)], soil C: N ratio differences among tillage [conventional tillage (CT) and no-tillage (NT)], burning (burn and no burn) and residue level (high and low), and soil electrical conductivity (EC) differences among irrigation (irrigated and dryland) and burning (burn and no burn) treatment combinations after 15 cropping cycles in a long-term wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

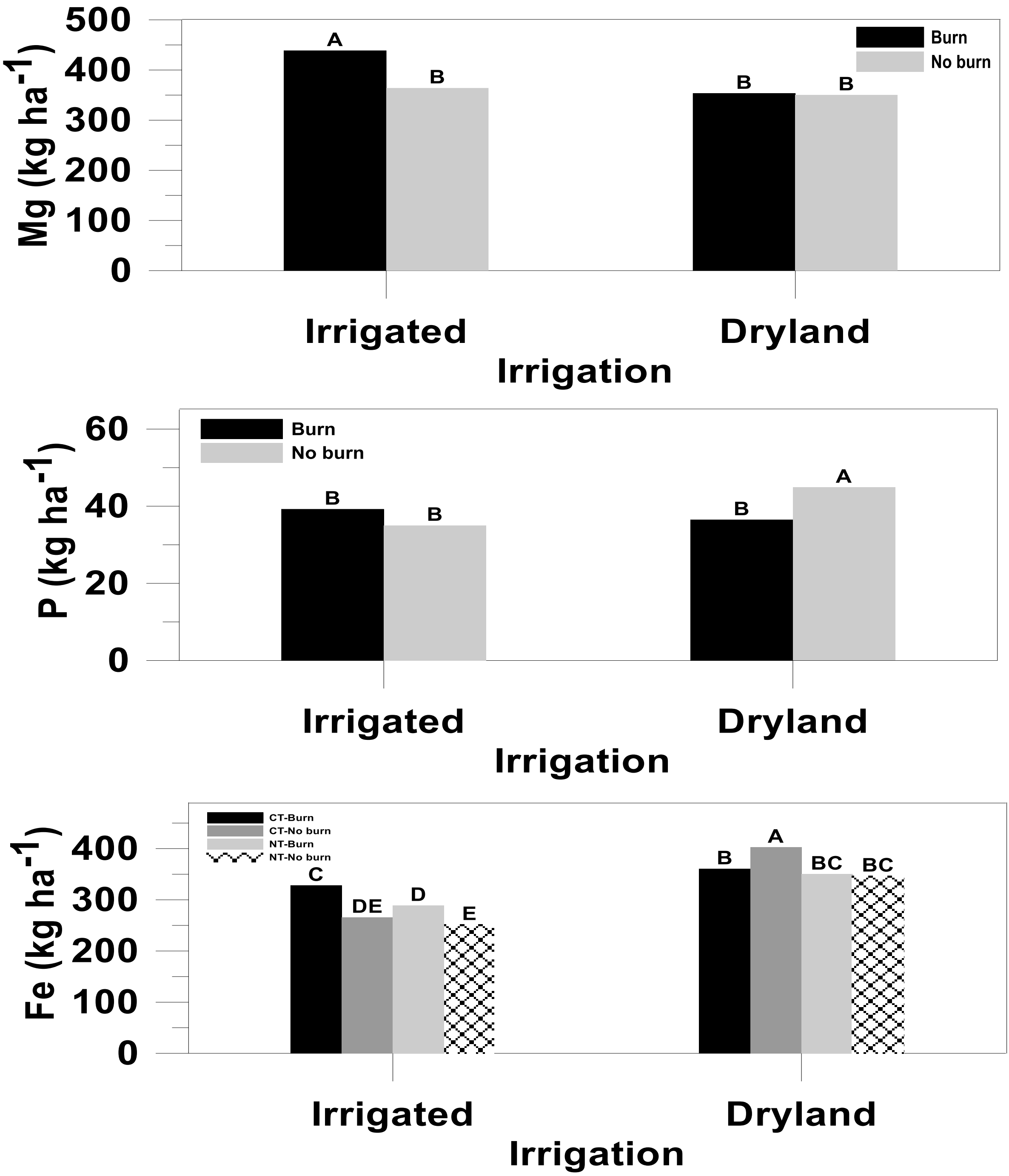


Figure 2. Extractable soil magnesium (Mg) and phosphorus (P) differences among irrigation (irrigated and dryland) and burning (burn and no burn) and extractable soil iron (Fe) differences among irrigation (irrigated and dryland)-tillage [conventional tillage (CT) and no-tillage (NT)]-residue burning (burn and no burn) treatment combinations after 15 cropping cycles in a long-term wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

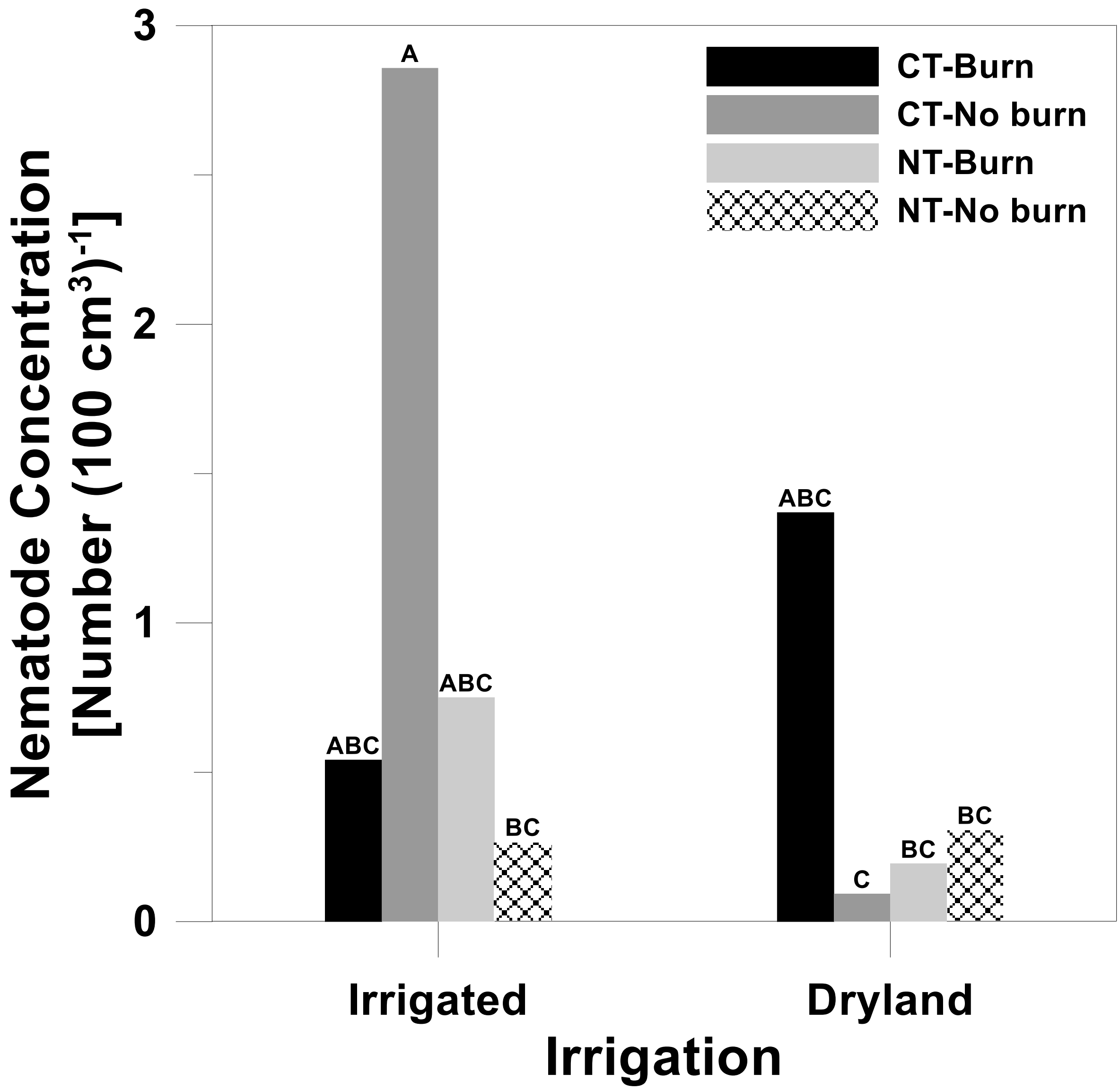


Figure 3. Soybean cyst nematode eggs concentration differences among irrigation (irrigated and dryland)-tillage [conventional tillage (CT) and no-tillage (NT)]-residue burning (burn and no burn) treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

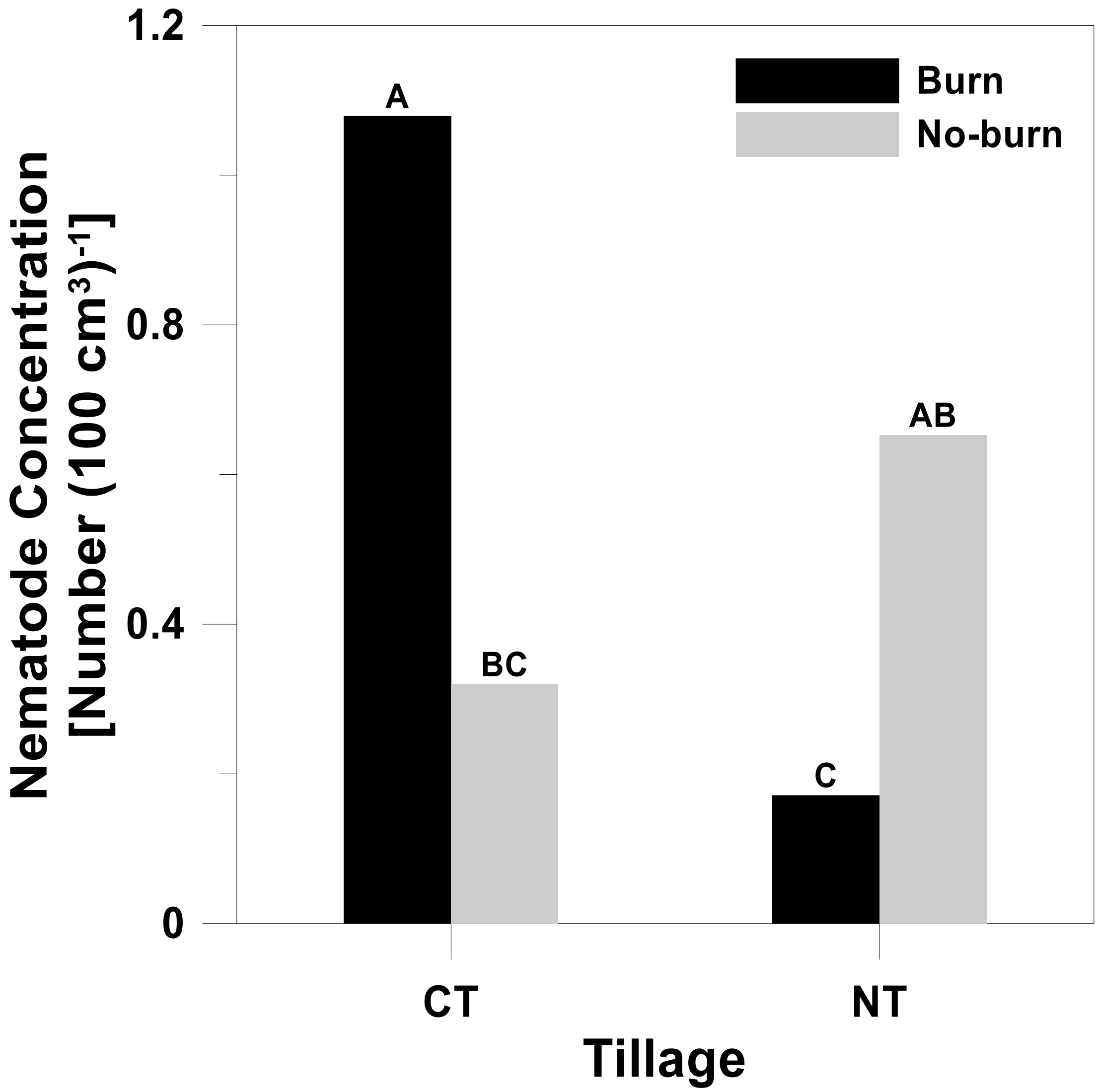


Figure 4. Soybean cyst nematode juvenile concentration differences among tillage [conventional tillage (CT) and no-tillage (NT)]-residue burning (burn and no burn) treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

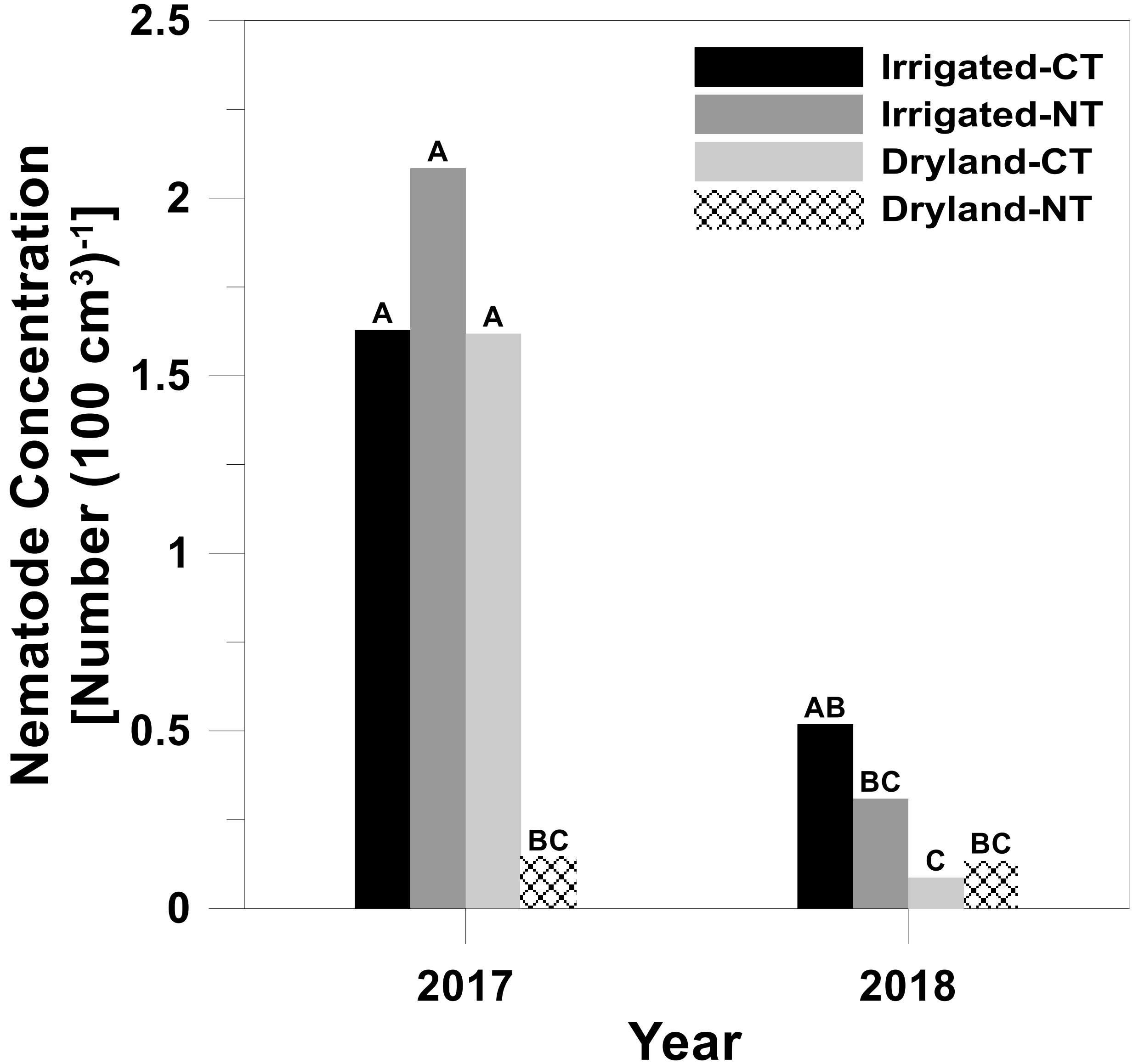


Figure 5. Soybean cyst nematode juvenile concentration differences among year (2017 and 2018)-irrigation (irrigated and dryland)-tillage [conventional tillage (CT) and no-tillage (NT)] treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

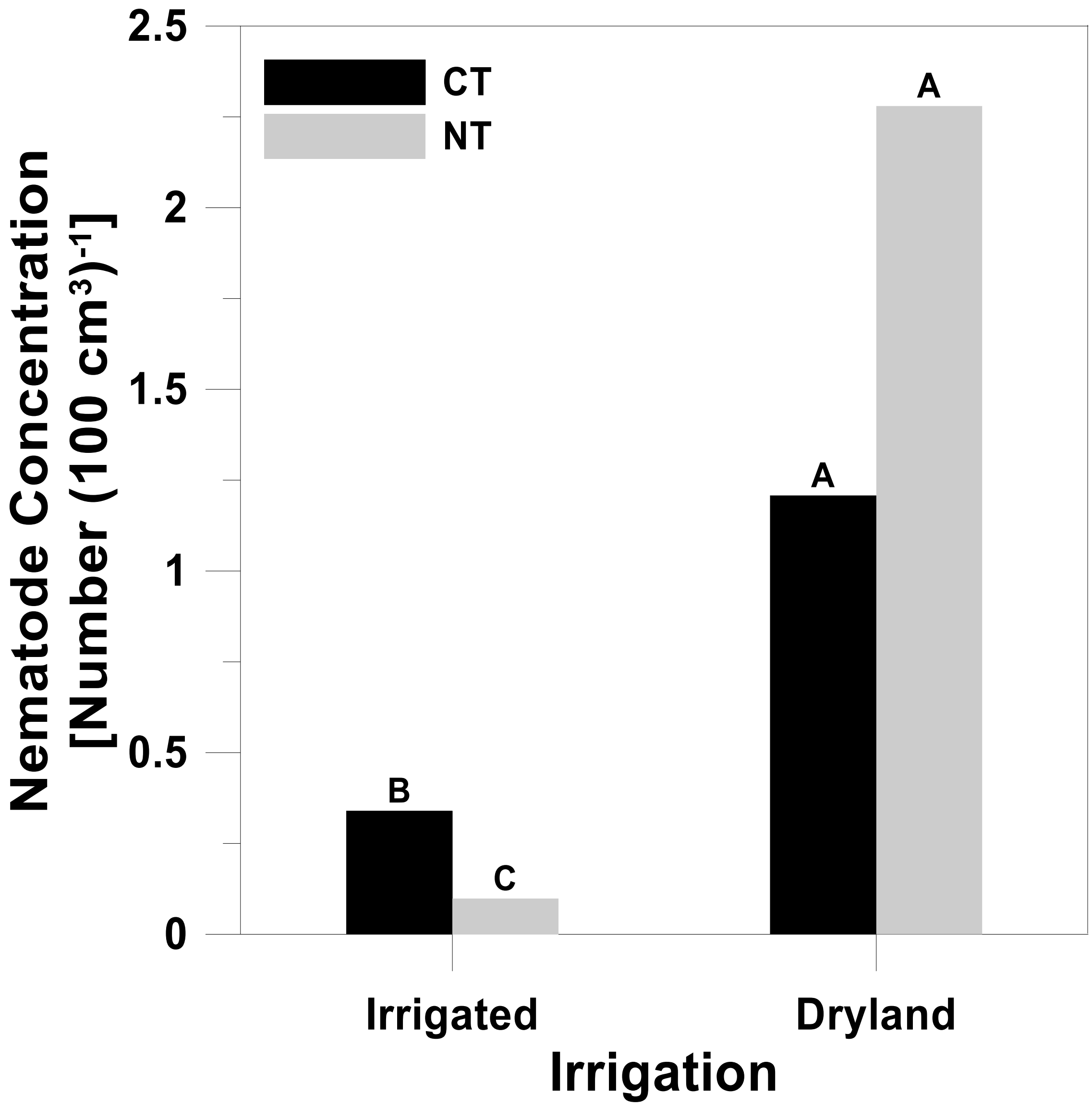


Figure 6. Lance nematode concentration differences among irrigation (irrigated and dryland)-tillage [conventional tillage (CT) and no-tillage (NT)] treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

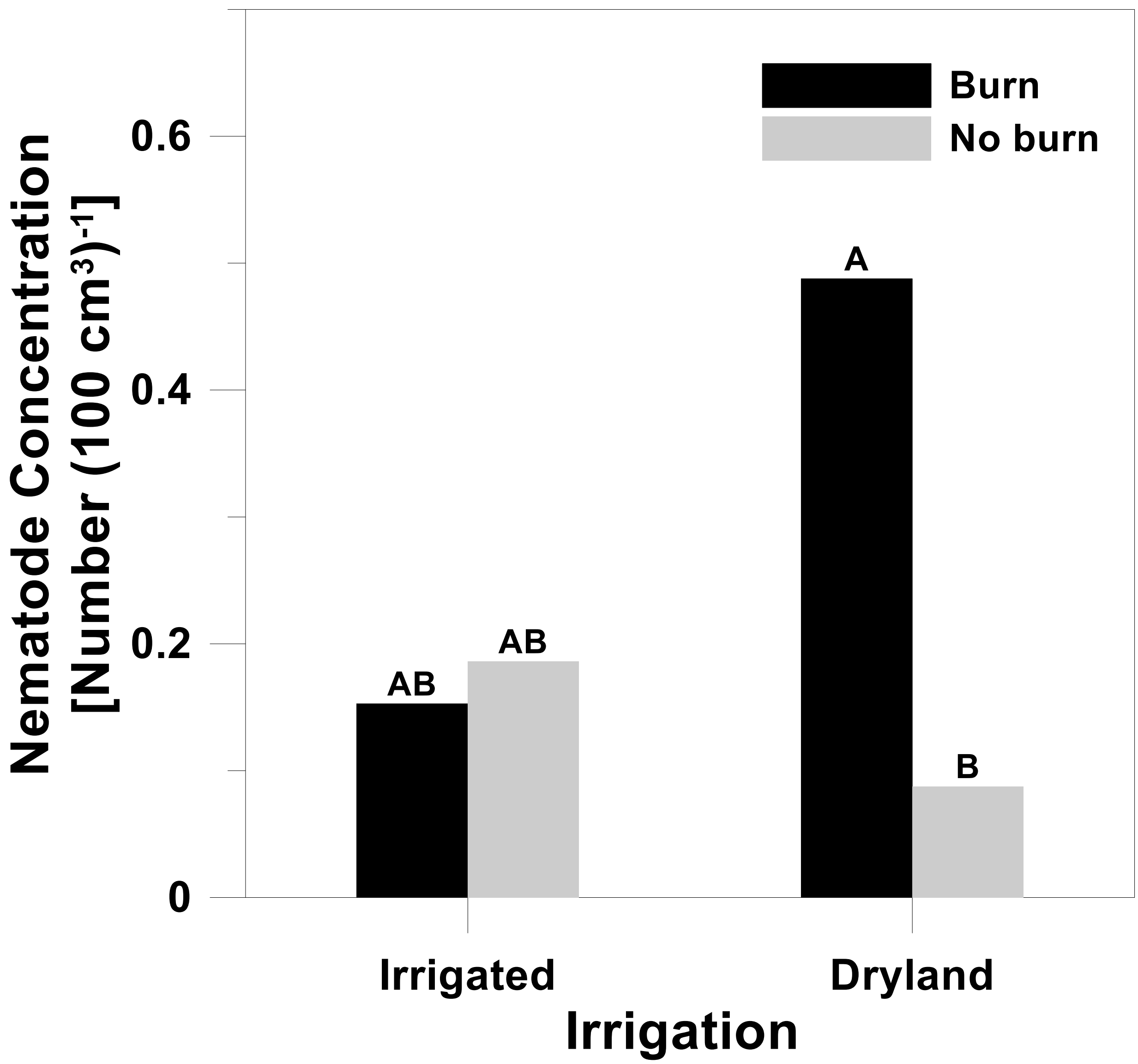


Figure 7. Lesion nematode concentration differences among irrigation (irrigated and dryland)-residue burning (burn and no burn) treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

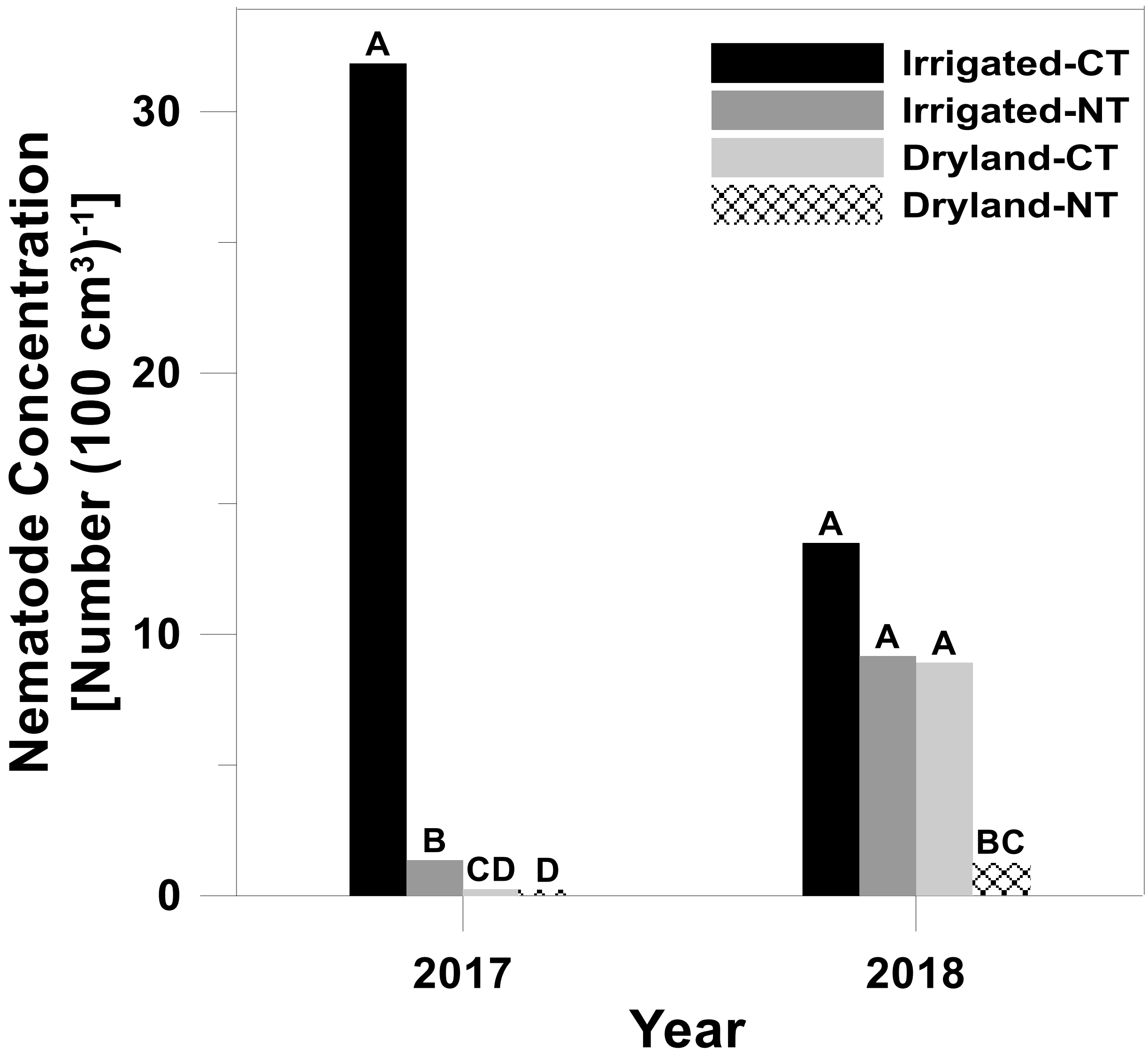


Figure 8. Spiral nematode concentration differences among year (2017 and 2018)-irrigation (irrigated and dryland)-tillage [conventional tillage (CT) and no-tillage (NT)] treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

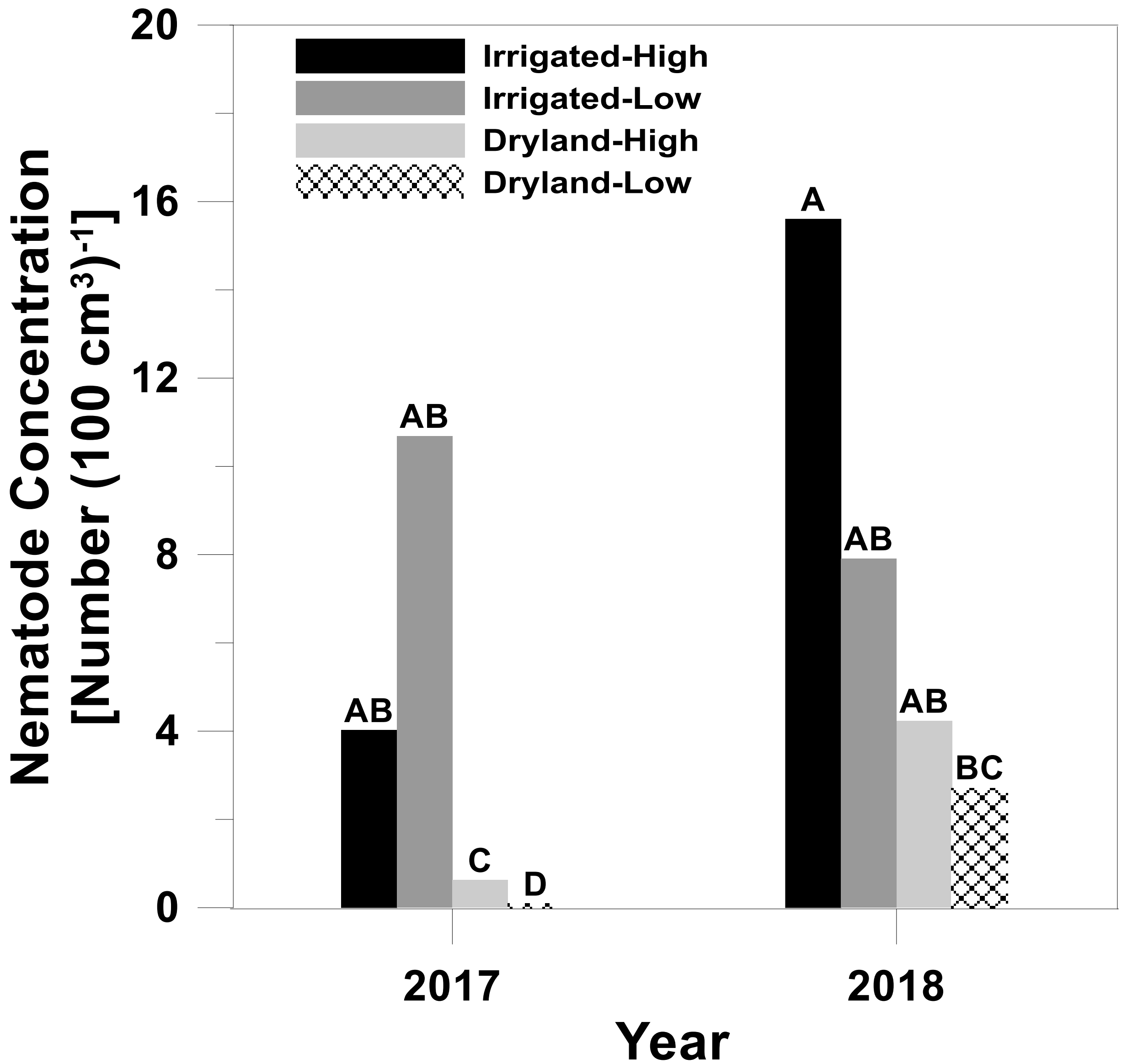


Figure 9. Spiral nematode concentration differences among year (2017 and 2018)-irrigation (irrigated and dryland)-residue level (high and low) treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

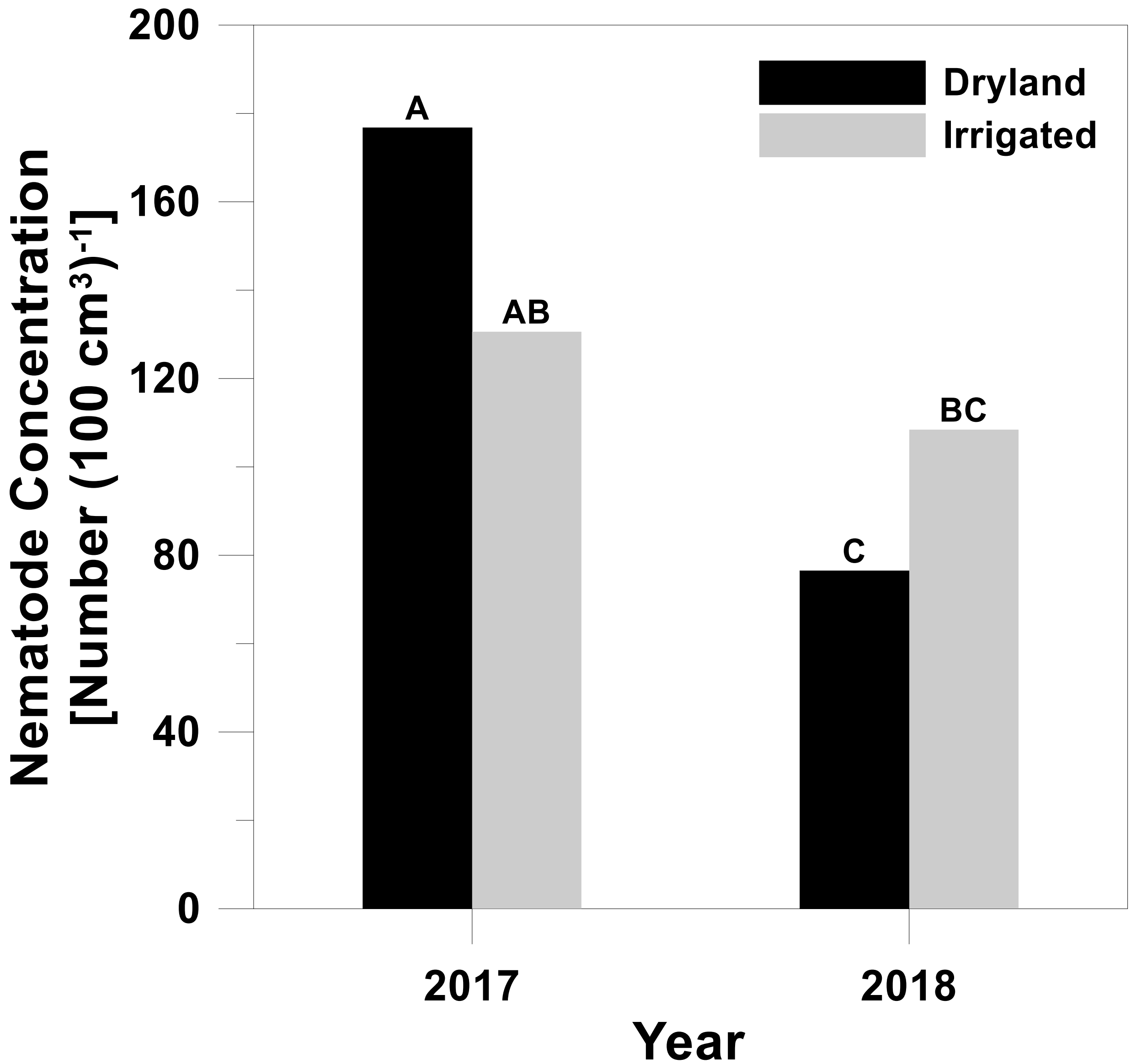


Figure 10. Total nematode concentration differences among year (2017 and 2018)-irrigation (irrigated and dryland) treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

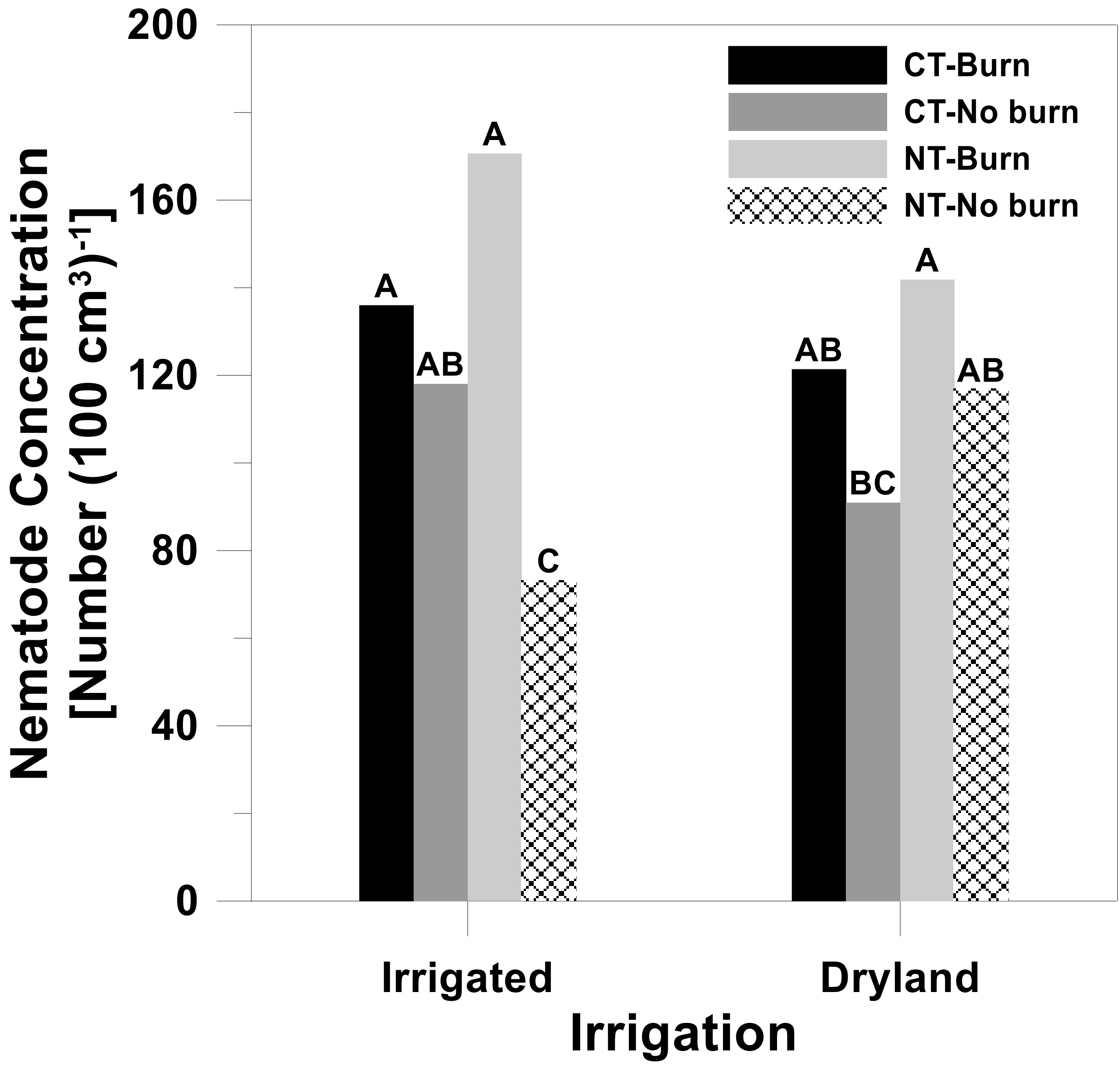


Figure 11. Total nematode concentration differences among irrigation (irrigated and dryland)-tillage [conventional tillage (CT) and no-tillage (NT)]-residue burning (burn and no burn) treatment combinations in a long-term, wheat-soybean, double-crop production system on a silt-loam soil in eastern Arkansas. Different letters atop bars are different at $P < 0.05$.

## Literature Cited

Alby, T., Ferris, J. M., and Ferris, V. R. 1983. Dispersion and distribution of *Pratylenchus scribneri* and *Hoplolaimus galeatus* in soybean fields. Journal of Nematology 15:418-426.

Allen T. W., C.A. Bradley, J.P. Damicone, N.S. Dufault, T.R. Faske, C.A. Hollier, T. Isakeit, R.C. Kemerait, N.M. Kleczewski, R.J. Kratochvil, H.L Mehl, J.D. Mueller, C. Overstreet, P.P. Price, E.J. Sikora, T.N. Spurlock, L. Thiessen, W.J. Wiebold, and Young. H. 2017. Southern United States soybean disease loss estimate for 2016. Pp. 3-8 in Proc. Southern Soybean Disease Workers, 44th Annual Meeting, Pensacola, FL.

Amuri, N., Brye, K. R., Gbur, E. E., Oliver, D., and Kelley, J. 2010. Weed population as affected by residue management in a wheat-soybean double-crop production system. Weed Science 58:234-243.

Arkansas Soybean Promotion Board (ASPB). 2019. Controlling harmful effects of nematodes [Online]. Available at: https://www.themiraclebean.com/controlling-the-harmful-effects-of-nematodes-2/ (verified 25 Nov., 2019).

Arnfield, J. A. 2019. Koppen Climate Classification. Encyclopedia Britannica Encyclopedia Brtiannica [Online]. Available at: http//www.britannica.com/science/Koppen-climate-classification (verified 26 Nov., 2019).

Baird, S. M., and Bernard, E. C. 1984. Nematode population and community dynamics in Soybean-wheat cropping and tillage regimes. Journal of Nematology 16:379-386.

Bao, Y., Neher, D. A., and Chen, S. 2011. Effect of soil disturbance and biocides on nematode communities and extracellular enzyme activity in soybean cyst nematode suppressive soil. Nematology 13:687-699.

Barker, K. R. 1985. Nematode extraction and bioassays. Pp. 19-35 *in* K. Barker, C. Carter, and J. Sasser, eds. An advanced treatise on *Meloidogyne*: Volume II, Methodology: Raleigh, NC, U.S: North Carolina State University Graphics.

Bridge, J., and Starr, J. L. 2007. Plant Nematodes of Agricultural Importance: A colour handbook. Manson Publishing. London, UK.

Brye, K. R., Cordell, L. M., Longer, D. E., and. Gbur, E. E. 2006. Residue management practice effects on soil surface properties in a young wheat–soybean double crop system. Journal of Sustainable Agriculture. 29:121-150.

Brye, K. R., Mersiovsky, E., Hernandez, L., and Ward, L. 2013. Soils of Arkansas. Arkansas Agricultural Experimental Extension, University of Arkansas System Division of Agriculture, Fayetteville, AR. 136 p.

Brye, K. R., Quarta, M., Morrison, C., and Rothrock, C. 2018. Long-term effects of residue and water management practices on plant parasitic nematode abundance and soybean root infection. Applied Soil Ecology 124:275-283.

Byrd, D., Barker, K. R., Ferris, H., Nusbaum, J. C., Griffin, W. E., Small, R. H., and Stone, C. A. 1976. Two semi-automatic elutriators for extracting nematodes and certain fungi from soil. Journal of Nematoly. 8 206-212.

Cordell, M., Brye, K. R., Longer, D. E, and Gbur, E. E. 2007. Residue management practice effects on soybean establishment and growth in a young wheat-soybean double cropping system. Journal of Sustainable Agriculture 29:97-120.

Emerson, M. Brown, K. Faske, T. R., and Kirkpatrick T. L. 2018. Field performance of several glyphosate-resistant maturity group 4 and 5 soybean cultivars in a root-knot nematode infested field. Pp. 40-41 in J. Ross ed. University of Arkansas Research Studies 2016. University of Arkansas Experiment Station. Fayetteville.

Go Soy. 2019. [Online]. Available at: https://www.gostrattonseed.com/assets/uploads/2018/03/20180309135920-84509-gosoy-pocket-folder-inserts-2018-proofpdf.pdf (verified 25 Nov., 2019).

Handoo, Z. A., Palomares-Rius, J. E., Cantalapiedra-Navarrete, C., Liébanas, G., Subbotin, S. A., Castillo, P.2014. Integrative taxonomy of the stunt nematodes of the genera *Bitylenchus* and *Tylenchorhynchus* (Nematoda, Telotylenchidae) with description of two new species and a molecular phylogeny. Zoological Jurnal of the Linnean Society 172:231-264.

Hartman, G. L., Rupe, J. C., Sikora, E. J., Domier, L. L., Davis, J. A., and Steffey, K. L. 2015. Compendium of soybean diseases and pests. The American Phytopathological Society. St. Paul, Minnesota, U.S.

Heatherly, L. G., and Young, L. D. 1991. Soybean and soybean cyst nematode response to soil water content in loam and clay soils. Crop Science 31:191-196.

Henneron, L. Bernard, L., Hedde, M., Pelosi, C., Villenave, C., Chenu, C., Bertrand, M., Cyril, G., and Blanchart, E. 2015. Fourteen years of evidence for positive effects of conservation agriculture and organic farming on soil life. Agronomy for Sustainable Development 35:169-181.

Hershman, D. E., and Bachi. P. R. 1995. Effect of wheat residue and tillage on *Heterodera glycines* and yield of double crop soybean in Kentucky. Plant Disease: 79: 631-633.

Jenkins, W. R. 1964. A rapid centrifugal-flotation technique for separating nematodes from soil. Plant Disease Reporter 48:692.

Kirkpatrick, T., T. Faske, T., and Robbins. B. 2014. Nematode management in Arkansas Soybean Production Handbook, MP197. University of Arkansas Cooperative Extension Service [Online]. Available at: https://www.uaex.edu/publications/pdf/mp197/chapter10.pdf. (verified 12 Aug., 2019).

Kirkpatrick, T. and Sullivan, K. 2016. Incidence, population density, and distribution of soybean nematodes in Arkansas. Pp. 47-49 in J. Ross ed. University of Arkansas Research Studies 2016. University of Arkansas Experiment Station. Fayetteville.

Kirkpatrick, T. 2017. Incidence, population density, and distribution of soybean nematodes in Arkansas. Pp. 72-73 in J. Ross ed. University of Arkansas Research Studies 2015, 637. University of Arkansas Experiment Station. Fayetteville.

Koenning, S. R., and Barker, K. R. 1995. Soybean photosynthesis and yields as influences by *Heterodera glycines*, soil type, and irrigation. Journal of Nematology 27:51-62.

Koenning, S. R., Overstreet, C., Noling, J. W., Donald, P. A., Becker, J. O., and Fortnum, B.A. 1999. Survey of crop losses in response to phytoparasitic nematode in the United States for 1994. Journal of Nematology 31:587-618.

Koenning, S. R., and Barker, K. R. 1995. Soybean photosynthesis and yields as influences by *Heterodera glycines*, soil type, and irrigation. Journal of Nematology 27:51-62.

Monfort, W. S., Kirkpatrick, T. L., and Mauromoustakos, A. 2008. Spread of *Rotylenchulus reniformis* in Arkansas cotton field over four-year period. Journal of Nematology 40:161-166.

Moore, W. F. 1984. Soybean cyst nematode. Soybean industry resource committee, Mississippi State University, Starkville, MS.

National Oceanic and Atmospheric Administration (NOAA). 2019. Data tools: 1981-2010 Normals, Arkansas [Online]. https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/climate-normals/1981-2010-normals-data (verified 26 Nov., 2019).

Norman, C. R., Brye, K. R., Gbur, E. E., Chen, P., and Rupe, J. 2016. Long-term management effects on soil properties and yields in a wheat-soybean, double-crop system in eastern Arkansas. Soil Science 181:1-12.

Progeny. 2019. [Online]. Available at: https://progenyag.com/wp-content/uploads/2018/10/5414LLS.pdf (verified 25 Nov., 2019).

Robbins, R. T., Riggs, R. D., and Von Steen, D. 1987. Results of annual phytoparasitic nematode surveys of Arkansas soybean field, 1978-1986. Annals of Applied Nematology 1:50-55.

Tucker, M. R. 1992. Determination of phosphorous by Mehlich 3 extraction. Pp. 6-8 *in* S. Donohue, ed. Soil and media diagnostic procedures for the southern region of the United States. Virginia Agricultural Experimental Station on Bulletin 374, Blacksburg, VA: Scientific Research.

Tyler, D. D., Overton, J. R., and Chambers, A. Y. 1983. Tillage effects on soil properties, diseases, cyst nematodes, and soybean yields. Journal of Soil and Water Conservation 38:374-376.

United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS).2017 State agriculture overview, Arkansas [Online]. Available at: https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=ARKANSAS. (verified 26 Nov. 2019).

United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS). 2019. Principal Area Planted – States and United States:2017-2019 [Online]. Available at: https://downloads.usda.library.cornell.edu/usdaesmis/files/j098zb09z/0k225n39n/jw827p632/acrg0619.pdf. (verified 12 Oct., 2019).

Wrather, J. A., and Koenning, S. R. 2006. Estimate of disease effects on soybean yields in the United States 2003 to 2005. Journal of Nematology 38:173-180.

Young, L. D. 1996. Yield loss in soybean caused by *Heterodera glycines*. Journal of Nematology 28:604-607.

**Conclusions**

Through assessing the natural nematode population densities in the soil on a wheat-soybean double-crop, this research has provided valuable understanding into the complexity of the effects of water and residue management on plant-parasitic nematodes. The objective of this investigation was to evaluate the combined long-term effects of tillage practice (conventional tillage and no-tillage), water management (irrigation and non-irrigation), residue burning (burned and non-burned), and wheat residue level (high and low) on the natural nematode population densities and reproduction in the top 10 cm within the growing season and between years soybean in a double-crop production system on a silt-loam soil in eastern Arkansas.
Wheat-soybean crop management affected nematode populations. The majority of nematodes studied were affected by at least one treatment or the interaction of two or more. Similar to what was hypothesized, nematodes population was generally greater under irrigation, CT, burn compared to dryland, NT, and nom-burn treatment, respectively. However, different treatment combinations did not have the same effect in all nematode species. Nematode management has to be tailored to species and agricultural practices for the best results.

# Appendices

**Appendix A**: Example of SAS program for evaluating the effects of tillage, irrigation, residue level, burning, date within growing season, and year on plant parasitic nematodes.

```
Title 'CBES Nematode Study 2017 2018';
options ls = 132 ps = 68;

data soil;
 infile 'nematode_data_sas.csv' firstobs = 2 delimiter = "," truncover LRECL = 600;
 input Plot $ Year $ Till $ Burn $ Res $ Irr $ Date $ Block SCNJ2 SCNEggs Lance Lesion Spiral
      Stunt Rootknot Dagger Ring Stubbyroot Reniform Total Species;
run;

ods rtf file = 'SCNJ2.rtf' style = journal bodytitle;

proc glimmix data = soil maxopt=100 pconv=1.0E7;
   class Year Block Irr Till Burn Res Date;
   model SCNJ2= Year | Irr | Till | Burn | Res | Date / ddfm = kr dist = poisson link = log;
   random block (Year) Irr*Block (Year) Irr*Till*Burn*Res*Block (Year);
   ods exclude FitStatistics InterHistory OptInfo;
   lsmeans Year*Irr*Till Till*Burn / lines ilink;
run;

ods rtf close;
```

**Appendix B**: Example of SAS program for evaluating the effects of tillage, irrigation, residue level and burning on soil physical and chemical properties.

```
Title '2017 SOIL PROPERTIES';
options ls = 132 ps = 68;

data soil;
 infile 'SOIL PROPERTIES 2017_NEW.csv' firstobs = 2 delimiter = "," truncover LRECL =
600;
 input plot till $ burn $ Res $ Irr $ pH EC bd Phos K Ca Mg S Na Fe Mn Zn Cu B
      TN TC CN SOM;
run;

ods rtf file = 'CN.RTF' style = journal bodytitle;

proc print data = soil;
run;_
quit;

proc glimmix data = soil maxopt=100 pconv=1.0E7;
   class Irr till burn Res ;
   model CN = Irr | till | burn | Res / ddfm = kr link = log;
   ods exclude FitStatistics InterHistory OptInfo;
   lsmeans Irr*till Irr*burn*Res till*burn*Res / lines ilink;
run;

ods rtf close;
```